Neotectonics and pastoralism: How they impact flood regimes in Madagascar's highlands

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Abstract

Sustainably maintaining the densely populated upland plains of Madagascar as operationally safe spaces for the food security of the nation and the urban growth of its capital city, Antananarivo, hinges critically on avoiding crop and infrastructure destruction by their through-flowing rivers. The flood regime, however, is also a function of two 'slow' variables hitherto undocumented: tectonic subsidence regime, and floodplain sedimentation rate. From a radiocarbon-dated chronostratigraphy and environmental history of the sediment sequences in three of Madagascar's semi-enclosed upland basins (Antananarivo, Ambohibary, and Alaotra), we quantify and compare how the precarious equilibrium between the two variables entails differentials in accommodation space for sediment and floodwater. Results show that all these plains have been wetlands for at least 40,000 years, but that the Antananarivo Basin is the most vulnerable because the imbalance between sedimentation and subsidence is the largest. Although the tectonic regime and the endemic forms of gully erosion that occur in the catchments are beyond human control, we advocate that flood mitigation strategies should focus on the natural grassland savanna, which makes up most of the contributing areas to surface runoff in the watersheds. Pastoralists are persistently left out of rural development programmes, yet the rangelands could benefit from the introduction of multi-purpose grasses and legumes known to withstand high stocking rates on poor soils while combining the benefits of nutritiousness, fire and drought resistance, with good runoff-arrest and topsoil-retainment abilities. Future-proofing Madagascar's upland grainbaskets and population centres thus calls for joined-up action on the sediment cascade, focusing on soil and water

sequestration through integrated watershed management rather than on hard-defence engineering against overflowing rivers on the plains, which has been the costly but ineffectual approach since the 17th century.

Key words: neotectonics; chronostratigraphy; flooding; urban sprawl; integrated watershed policy; rangeland management

1. Introduction

Strategies and institutions of governance and development interact with the conditions and process regimes set by geology, hydrology, ecology, geomorphology and climate. In addition to being products of the contingent biophysical processes that shape the Earth, landscapes are thus also the product of power relations and other disparities. As a discipline, geography has long embraced the unity of social science and physical landscape change in the service of social and environmental transformation, but the recently branded concept of 'critical physical geography' (Lave et al., 2014) also reminds us that there is an underlying political economy of processes such as soil erosion, land-cover change, natural hazards, and disaster mitigation strategies. Studies of the total environment thus gain from perspectives which combine expert knowledge of biophysical science and technology with critical attention to political ecology, i.e. to relations of social power in which some voices get silenced while others get amplified. These many variables are often difficult to untwine, but for environmental policymaking purposes it is essential that they be unpacked and diffracted in ways that help to convey a just and lucid portrayal of the total environment.

The creation of sustainable, safe, and socially just operating spaces for socio-ecological systems is commonly a goal intended to achieve wellbeing for all while simultaneously ensuring that the underpinning biophysical processes and environmental services are exploited within scientifically informed boundaries of sustainability (Dearing et al., 2014;

Hossain et al., 2017). The concept of ecologically safe and socially just spaces has been addressed at global level in generic terms through the 'planetary boundaries' concept (e.g. Rockström et al., 2009), but less so at regional levels such as watersheds, wetlands, and other coherent natural units where the dissemination of policymaking based on an integrated understanding of complex interactions really matters to communities.

Floodplains, for example, which may contain permanent wetlands and temporary lakes, are valued for their biological productivity, and for the ecosystem services and other natural resources they provide, but they are also coveted for agriculture. In the midst of a mountainous island-continent and one of the poorest countries in the world, the upland intermontane basins of Madagascar's Highlands have historically been developed and managed for the purpose either of rice monoculture or more diversified cropping systems (Abé, 1984). The Highlands, or Hautes Terres, which in Madagascar refer to the elevated backbone of weathered Precambrian basement, concentrate 45% of the nation's population of ~25 M (in 2016). This core zone of the island's interior (~130,000 km^2, i.e. 22% of the island; elevation range: 800–2800 m; mean annual rainfall: 1200–1500 mm) features population density clusters of > 250/km^2 in and around the intermontane basins. Such has been the case consistently for at least ~100 years (de Martonne, 1911; Gourou, 1967). Following a sharp rise since the late 1990s, the population of the capital city's metropolitan area, Antananarivo, reached 3 M in 2015 and is now recording an annual growth rate of 4.6% (Attoumani et al., 2019; Defrise, 2020). The Highlands are physically and culturally separate from the wide band of sedimentary scarplands forming the west of the island (Fig. 1), which corresponds to an area of dry forest, scrub and pseudo-steppe dominated by extensive pastoralism. It is, by comparison, very thinly populated (< 25/km^2, and often < 4/km^2).

The interior basins of the Highlands are primarily natural wetlands (typically fens: Mietton et al., 2018), and as such have been attractive for their level topography and their potential for paddy cultivation. Wetlands, however, are transient features at geological time scales and their life span can be substantially shortened by human action in the catchment — either by changing the hydrological balance (e.g. excessive water abstraction by an irrigation scheme, or excessive outlet release) or by sediment overfilling the basin's accommodation space (e.g. as a result of excessive soil erosion in the surrounding catchments). At shorter time scales of years to centuries, the persistence of sufficient accommodation space to avoid lake or wetland extinction depends on a fine balance depending on how processes governing the lithosphere, biosphere, atmosphere and hydrosphere intersect with the anthroposphere (Lisenby et al., 2019). Wetland persistence is typically a function of geometrical constraints (initial relief, length of the river, hypsometry of the catchment), lithological parameters (rock erodibility), climate (precipitation and evaporation rates), and — often neglected or harder to quantify — the relatively slow (and thus imperceptible over years and centuries) rate of tectonic subsidence and crustal deformation (i.e. uplift rate, duration, and its spatial distribution; see Graphical abstract). Modelling of tectonics-controlled inland lakes shows that once uplift declines and/or lake or wetland capture is achieved by headward drainage recession, the upland wetlands risk getting reintegrated into the drainage network and drying up (Garcia-Castellanos, 2006).

Lisenby et al. (2019) have emphasized that existing wetland characterisation tools tend to neglect geomorphology, so that managers or development agencies who rely on them may build up an incomplete set of expectations regarding the characteristic processes, forms and timescales of wetland and floodplains dynamics. This may be particularly problematic where this dynamism occurs on management-relevant timescales of years to decades because incorporation of geomorphological perspectives into management planning and practice can improve understanding of the relative importance of natural and anthropogenic drivers of wetland change, and thus help to decide when, and when not, to intervene.

Among the rice-growing areas of Madagascar, the central Highlands are the region where the rainfall conditions are seasonally best adapted to rice growth despite constraints relating to low winter temperatures (Le Bourdiec, 1974). Annual rainfall totals range between 1000 and 1500 mm and occur during the warmer season (November to April). This is also, however, the most mountainous and topographically fragmented part of the island, so that the optimal areas for high-yield paddy cultivation are restricted the flat-floored intermontane basins — often of limited size (Bied-Charreton et al., 1981). Importantly, most of these upland plains result from impeded drainage controlled by some form of bedrock constriction at the exit point, either because of tectonic faulting, of a lava dam, or a combination of both — which to varying degrees has promoted water ponding and sediment aggradation. The geomorphological behaviour of these outlets is what promotes the alluvial aggradation and poor drainage potentially advantageous to human settlement and paddy cultivation, but only on condition that the intensity of these processes can be maintained within a certain critical bandwidth of variability. The wetland base levels and hydrological regimes are thus subtly controlled by tectonic faults, by basement rocks with differing sensitivities to differential erosion, and by the varying intensities of topographic incision by rivers (Raunet, 1980).

Although the tectonic and fluvial regimes in Madagascar are difficult to measure or monitor directly, a chronostratigraphy of the sediment retained in the wetland basin should provide a proxy of how long this regime has been sustained, and at what rate. The waterlogged wetlands contain clay-rich sediment and weakly decomposed (and thus radiocarbon-datable) organic matter such as peat. Insights obtained from sediment coring and trenching can thus provide long-term baseline information for underpinning an integrated, basin-scale management strategy of the total environment that avoids short-sighted, sectorial measures such as unplanned urbanisation (Dabat et al., 2004; Aubry et al., 2012; Defrise, 2020), short-sighted hydraulic engineering, and detrimental land-use policies.

By comparing different Highland basins with somewhat different characteristics, in this study mainly focused on the Antananarivo Plain we show how tectonic, hydrological, sedimentological and palaeoenvironmental variables have played out over the last several thousand years prior to human settlement, and how engineering and human agency in the last ~100 years have been interfering — and could interfere critically in the future — with the baseline trends. We thus gauge and analyse the boundaries to sustainability of these key rice-growing basins (Fig. 1) which, as the new evidence suggests, hinge on a finely balanced long-term equilibrium between tectonic regime, sedimentation rate, and cumulatively evolved socio-ecological practices which control soil erosion in the wider tributary catchments and their nested sub-catchments.

This kind of multidisciplinary and integrated approach to watershed management, articulating the biophysical and the social sciences while including a long-term historical dimension, reframes the technocratic approach to river flood-hazard modelling which, by focusing unilaterally on simplified channel hydraulics and on the short-term prospect of constructing hard defences at locations where the flooding occurs (often calibrated on limited hydrological time series datasets), inflates the playbook that large engineering corporations have been writing for the last ~200 years while missing two key points: these sectorial risk-reduction planning approaches (i) expediently ignore the important dimension of political ecology, and (ii) historically have often failed to meet the targets of their own forecasts (both aspects comprehensively critiqued in McCully, 2001).

As an alternative perspective, the holistic approach explored in this study paves the way towards a form of systemic thinking among environmental managers that also allows room for participatory methods rather than the conventional, top–down technocratic solutions. Holistic thinking along these lines has gained some traction through the relatively recent 'ecosystem services' paradigm, with perhaps the most famous operationally successful example being the conservation of urban water quality in the Catskills/Delaware watershed for the benefit of the city of New York based on a ‘payment for ecosystem services’ (PES) scheme. The scheme grew out of public consultation and was guided by the motto “we all live downstream”, including stakeholders who actually reside and operate in the catchment headwaters (see “How to put a watershed to work”, in Daily and Ellison, 2002).

Such ‘success stories’, however, still today remain rare almost anywhere, and in an economically poor country like Madagascar these approaches are in their infancy at least partly because agencies involved in environment and land issues tend to promote sectorial rather than integrated solutions. This study thus puts Madagascar and its state capital on the global map of research into integrated watershed management — in the present case showing how curiosity-driven research on tectonics and past environments ties in with policy-driven research. Furthermore, whereas conventional flood-mitigation policies in most biomes typically advocate planting trees as a natural means of promoting water infiltration over runoff (this can range from state-controlled, single-species protection forest, to more participatory forms of agroforestry: e.g. Aryal et al., 2019), we emphasise instead the importance of bespoke, place-based solutions through a holistic consideration of geomorphological, hydrological, ecological, but also cultural components of Madagascar’s environment. In the case of Madagascar’s central Highlands, where the natural vegetation is overwhelmingly not forest but grassland savanna or pseudo-steppe (see Graphical abstract), afforestation is actually neither a natural solution nor a culturally accepted one. Instead, we consider the importance of pastoralism, forage, and fire in these landscapes where the economic, cultural, and environmental footprint of pastoralists and their livestock is substantial, but where these socially marginal stakeholders are recurringly ignored by rural development programmes, which focus on farming and forestry.

The rationale and successive steps of the methodology are summarised by a flow diagram presented in Figure 2.

2. The Antananarivo Plain: its key features

2.1. Hydrology

The Antananarivo plain (~162 km^2, 1247–1255 m a.s.l.) lies in the upper Ikopa River basin (catchment area above the Farahantsana channel knickpoint: 4466 km^2; Fig. 3). The intermontane basin operates as the local base level for a number of left- (Sisaony, Andromba/Katsoaka) and right-bank tributaries (Mamba, Maniandro), all of which converge on the plain. Stream convergence is frustrated by the fact that the Ikopa River has been continuously or partially constricted by artificial levees over a distance of 45 km, as far as Bevomanga. The Sisaony River in the early 20th century used to join the Ikopa at Anosizato (Fig. 2; Isnard, 1955). The Ikopa channel gradient is very gentle (~0.00025), and decreases to 0.00013 just before the junction with the Andromba River. From the Bevomanga 'narrows' to the Farahantsana knickpoint (Fig. 4), the Ikopa flows in a bedrock channel. The river then plunges 50 m down a gorge displaying a succession of rapids and waterfalls, and eventually joins the Betsiboka and the Mozambique Channel.

Only part of the interior wetland has been converted to farmland. Reclamation of what was initially a periodically flooded mosaic of scrub and marshland began in the 17th century under the authority of the Merina monarchs (at first under King Ralombo, 1575–1610; but mostly under King Andrianampoinimerina's reign: 1785–1810; see Abé, 1984), ostensibly at a time of enhanced rainfall (1500–1850 CE) compared to the preceding 500 years — but nonetheless containing a nested sequence of multi-decadal rainfall fluctuations documented within that time span (Scroxton et al., 2017). These early efforts, aided by copious availability of slave labour (Raison, 1986; Larson, 2000; Campbell, 2005), focused on the right bank of the

Ikopa River, where the Ankadimbahoaka levee, or ‘embankment of the people’, was constructed. The plain, progressively criss-crossed by 200 km of canals (often multipurpose: for drainage, irrigation and navigation), was given the name Betsimitatatra, meaning ‘that which no longer needs reclamation’ (for a detailed historical geography, see Isnard, 1955; Raison, 1972; Douessin, 1974). The Farahantsana bedrock sill partially closes off the basin and causes in-channel bedload deposition upstream. As a result, the channel bed has risen between its levees to elevations greater than the surrounding plain, thus causing frequent levee breaching, crop inundation, and flooding of the capital city’s low-lying sprawl. Raising the levees incrementally has simply perpetuated the flood hazard issue in a self-reinforcing feedback loop.

With new technology — particularly explosives in addition to manpower — the colonial authorities introduced two additional measures.

(i) In order to reduce the perennial risk of flooding, the Ikopa underwent channel deepening aimed at hastening floodwater evacuation, limiting water pressure against the levees, and with benefits also expected for the vulnerable residential areas of Antananarivo. The first blasts along this 5-km-long reach were carried out around Farahantsana in 1914, then in 1938 and 1940 — deepening the channel by 1.6 to 3 m over a width of 80 m, thereby also steepening the channel gradient (Ciolina, 1946; Isnard, 1955). An estimated 430,000 m^3 of rock were removed, among which 170,000 m^3 of bedrock. A wave of headward erosion soon ensued, clearing the channel of its sediment, exposing the bedrock in new reaches, and thus effectively extending the knickzone upstream to Bevomanga. An accompanying measure was to build a needle dam further upstream (Tanjombato Dam) as a means of raising the hydraulic head by ~1.4 m to irrigate some of the higher land traditionally devoted to second-season cropping.

(ii) The second major undertaking was the construction of the Mantasoa (1938) and Tsiazompaniry (1956) dams (125 and 260 M m^3 design capacities, respectively), designed for hydroelectricity and both flooding a network of valleys in the remote headwaters of the Ikopa catchment near the island's continental drainage divide (Fig. 3). The expectation was that these reservoirs would also retain excess water during the rainy season and reduce the flood hazard, as well as ensure low-flow augmentation (by 5–12 m^3/s) for securing dry-season irrigation.

The frequent flooding today in Antananarivo strongly suggests that the engineering works of the past century were of limited avail. Catastrophic flood damages reported for Jan.–Feb. 1917 (Chaperon et al., 1993) recurred in Feb. 1932 (peak flow measured at Bevomanga gauging station: 600 m^3/s), March 1941, Jan. 1954, and March 1959. Benchmark records from 1948–49 to 1976–77 at Bevomanga document annual peak discharges consistently in excess of 250 m^3/s on the Ikopa River, with a record maximum of 642 m^3/s measured on March 31st, 1959, and an estimated 1750 m^3/s at Farahantsana (Anonymous, 1965). As with most regulated rivers, artificial levees are merely a relative solution to flood-hazard mitigation because they force in-channel sediment load deposition, thus raising the channel bed and waterline. This promotes levee breaching and channel overspill. Accidental overspills present the advantage of reducing instantaneous maximum discharge at locations situated downstream, and this is confirmed for the Ikopa River: it records greater peak discharge maxima where it enters the plain at Antelomita (upstream of Antananarivo: e.g. 710 m^3/s on March 31st 1959) than near its exit at Bevomanga. Neither of the two headwater reservoirs have thus proved effective at curbing flood peaks on the Ikopa.

The hydrological hazard is exacerbated by cyclones making landfall on central Madagascar, particularly when these occur towards the end of the rainy season on swollen water tables and saturated lowland soils. As a result of the flooding, rice yields in the

Antananarivo plain can fluctuate by up to 50% from one year to the next (Dabat et al., 2004), thus increasing dependency on imports. Flood hazards are also exacerbated by Antananarivo's urban sprawl across the surrounding flood-susceptible paddy fields (Aubry et al., 2012; Ciampalini et al., 2019). During the colonial period, 22 ha of marshland were reclaimed and landfilled to develop the new district of Analakely and open the (now renamed) Avenue de l'Indépendance, inaugurated in 1935. Both now lie at the heart of the city (Fig. 5). During that same period, and despite being 'protected' by river levees, expanding slums on the west side (mostly established on shoddily and illegally reclaimed wet-rice cropland) soon became insalubrious and exposed to flooding because of a backwater effect caused by excessive in-channel sediment aggradation around Bevomanga. The entailing rise in water levels upstream of Bevomanga also exacerbates lateral pressure on the Ikopa levees (similar effects occur simultaneously on the Sisaony and Andromba rivers), and thus the frequency of breaching and floodplain spills occur even before the peak flood wave on the Ikopa enters the plain. Today, floodwater evacuation is impeded by the unfettered increase in paved surfaces and chronic obstruction of the low-gradient stormwater drainage systems by urban detritus and by the insufficient hydraulic head between the urban drainage and the Ikopa River base level.

2.2. Geological setting

2.2.1. Lithology

The Antananarivo Basin lies at a structural node in the Precambrian fabric of the basement known as the Antananarivo virgation zone (Nédélec et al., 1994), a twist in the Panafrican orogen where the strike of the stratoid granites changes from N–S to E–W.

Most of the Ikopa catchment area consists of migmatites and gneiss, with a few outcrops of plutonic granite (Carion Massif, Behenjy Massif), stratoid granite (Nédélec et al., 2000), and minor charnockite (Fig. 6). The highest summits of Antananarivo's urban topography coincide with ridges reinforced by quartzite beds, outcrops of which also strike across the Farahantsana bedrock sill. The basement south of the Antananarivo Basin is covered by the volcanic rocks of the large Ankaratra volcano and various satellite intrusions. Ankaratrite flows (nepheline basanite) 20 km to the SW of Antananarivo (e.g. Delubac et al., 1963) were generated by the small Vontovorona volcano (Fig. 6). The sediment fill of the basin itself remained relatively undocumented until recent excavations in the context of urban construction projects. The material is largely of an alluvial nature and described in this study.

2.2.2. Evidence of neotectonics

Despite the great antiquity of the basement rocks and the deceptive assumption of stability often associated with Precambrian shield regions, the topography of central Madagascar is extremely youthful. The main cause of base-level change was late Cenozoic (Neogene) crustal uplift, mostly as a result of sub-lithospheric mantle convection beneath Madagascar causing crustal buoyancy, regional-scale updoming, and intraplate volcanism. Supporting evidence for this has been provided by several lines of research. In addition to the well-established succession of erosion surfaces in the Highlands (Bourgeat and Petit, 1969), which suggests base levels falling in successive steps in response to regional uplift, fission-track data likewise suggest that rapid regional uplift and denudation commenced within the last 20 Ma (Stephenson, 2019). Delaunay (2018) and Roberts et al. (2012) used the distribution of erosion surfaces and inverse modelling of river longitudinal profiles, respectively, to also conclude that Madagascar had undergone wholesale regional uplift during the last 15 Ma. A remarkable feature of most rivers in Madagascar is indeed that none display typical concave-up equilibrium profiles. Instead, they exhibit distinct convex profiles interrupted by a large number of knickzones and waterfalls typical of disequilibrium conditions driven by tectonic activity (Fig. 4).

Additionally, the present-day elevation of the crust is anomalously high despite its lower-than-normal thickness evidenced by gravity and seismic data (Rechenmann, 1981; Fourno, 1990; Rakotondraompiana, 1992). Independent tomographic and petrological evidence confirms that the epeirogenic uplift of Madagascar can be accounted for by the existence of a layer of anomalously hot asthenospheric mantle directly beneath a thin lithospheric plate (Rindraharisaona et al., 2013; Andriampenomanana et al., 2017; Stephenson et al., 2019). The upwelling asthenosphere provides the dynamic support needed for maintaining the elevated topography.

Consistent with these broad-scale geological findings, seismicity is also an important feature of central Madagascar, where 97% of the island's thousands of earthquakes occur annually. No fewer than 3346 earthquakes with a magnitude greater than 3.0 were recorded between 1975 and 2007, mostly associated with extensional faulting (Rindraharisaona and Rambolamanana, 2008). The most active area lies beneath the late Neogene to modern Ankaratra and Itasy volcanic edifices (Hariniony, 2018), barely 50 km SSW of Antananarivo (Figs. 1, 3), where 658 events were recorded just between 2003 and 2016 and registered peak magnitudes of M_L 6.1 (typically at shallow crustal depths of 15–30 km). Although some of these could be related to subsurface magmatic activity, a much larger, nonvolcanic seismic sub-region immediately to the north (so-called 'Famoizankova seismic region'), effectively adjacent to, and west of, the Antananarivo study area, recorded 104 seismic events during that same period, with an even higher peak event registering at M_L 6.4 (Hariniony, 2018). On nonvolcanic rocks of the Highlands, surface expression of the recent and ongoing crustal deformation has been inferred from gully erosion ('lavaka', from a word meaning 'hole': spectacular gullies on hillsides, see Graphical abstract), showing that high-density lavaka 'hotspots' coincided spatially with foci of more intense seismicity (Helisoa, 1983; Cox et al., 2010). The intensity of hillslope dynamics could thus be a response to, and thus used as a proxy for, the magnitude of tectonic deformation.

Unlike the Alaotra Basin (Fig. 1), which geologically is an active tectonic graben (Mietton et al., 2018), the Ikopa catchment and the Antananarivo Basin do not correspond to one of these lavaka hotspots. The digitations of the Antananarivo Basin (Figs. 3, 6) primarily suggest its origin as an etch basin, i.e. a lowland originally generated by differential weathering in petrographically heterogeneous or diversely fractured basement outcrops (e.g. Lageat and Gunnell, 2001) rather than by tectonics. The low hills and interfluves rising from the plain correspond to the late Neogene erosion surface 'S3'. As elsewhere in the Highlands, (i) its elevation (here ~1300 m) is controlled by a local, non-marine base level set by the bedrock sill on the trunk river; and (ii) it has developed across lithologies highly susceptible to decay under intense tropical weathering conditions, such as schist, gneiss and migmatite (Bourgeat and Petit, 1969; Hoeblich and Hoeblich, 1983). Accordingly, the interfluves are blanketed by ~30-m-deep Ferralsols.

Despite not displaying the first-order morphological features of a faulted graben, the Antananarivo Basin nonetheless displays features suggesting neotectonic overprints. In addition to a major E–W Precambrian shear zone cutting across the basin (e.g. Nédélec et al., 2016), these include:

(i) a NE–SW fault which cross-cuts the Anjafy–Angavo anticline from north of the Ankay to south of Antananarivo. This fault probably continues beneath the Ankaratra volcanic cover and eventually intersects the Vavavato and Ibity faults farther west (Fig. 1);

(ii) a NW–SE lineament guiding the drainage net, one of several in the wider region and parallel to the major, elongated seismicity hotspot identified by Cox et al. (2010) farther to the west, consistent with NE–SW fault-solution mechanisms inferred for the

Itasy, Ankaratra, and Famoizankova seismic subregions (Barimalala and Rambolamanana, 2008);

(iii) a series of N20° to N30°E structures north of the Antananarivo Basin (around the small town of Mahitsy), reported on the basis of microtectonic observations in a quarry (Arthaud et al., 1990; Dussarrat, 1994) and also reported as locally offsetting weathering profiles. This strike direction also has an important influence on the local drainage network, and may bear some connection with a long E–W lineament mapped by Rakotondraompiana (2001) and passing along the north edge of the Antananarivo Basin.

(iv) Brenon (1952) speculated that the Ikopa plain had formed because of a tectonic block rising across its path, and Bourgeat (1968) interpreted it as a downthrown block east of the tentatively named N–S 'Imerintsiatosika–Antambola line' (Fig. 3) — perhaps a tectonic lineament, despite the fact that the geology of this region west of the capital city has never been mapped. Fourno (1990) likewise accredits the hypothesis of a tectonic origin for the Antananarivo Basin.

Dussarrat (1994) tentatively estimated that the E–W faults were younger than the N–S set because microtectonic striations generated by the N–S extension were cross-cut by striations generated by the E–W extension. The E–W fault movements were most likely late Pleistocene (i) because small vertical offsets were reported from the 25–10 ka alluvial deposits (Bourgeat, 1968; Bourgeat and Ratsimbazafy, 1975), and (ii) because those faults did not offset peat layers of early Holocene age (9–2.6 ka) — the latter only estimated, however, by intuitive correlation of the peat with an independently established period of climatic stability (e.g. Burney, 1987) rather than by direct dating.

In summary, tectonic deformation in the Highlands of Madagascar is geologically recent, and seismicity is low- to medium-intensity and ongoing. Crucially, the link between sedimentation, hydrological regulation, land use, and tectonics becomes critical upstream of where the Ikopa River exits the basin.

3. Methods

The sedimentary fill sequence of the Antananarivo Basin lacks natural sections, and quarries in weathered profiles do not reach the bedrock. As a result, the stratigraphy beneath the alluvial plain had until now never been investigated. The need to survey the subsurface has nonetheless grown from increasing demand for high-rise urban construction and as part of hydrogeological exploration for supplying the city with water. In clay-rich sequences, electrical surveys are less efficient than electromagnetic surveys for detecting depths to the bedrock floor because of backscatter effects. Mechanical trenches and boreholes remain the best source of information. Recent drilling operations have cored mostly through clay and sand-rich layers (rarely loam), but significantly also through a number of peat levels.

Here we collected, compiled and correlated unpublished data from recent civil engineering studies, and from reports by geologists: 3 construction-drill auger cores < 10 m deep (BRL Ingéniérie, 2018), 1 test pit reported by Bourgeat and Ratsimbazafy (1975), and 14 boreholes up to 30 m deep (sources: Colas; Laboratoire National des Travaux Publics et du Bâtiment; Laplaine, 1957; Rakoto et al., 2017). The goals were to estimate the thickness of the sediment fill in the Antananarivo Basin, characterise its stratigraphy, constrain its depositional age, and infer time-averaged sedimentation rates upstream of the Farahantsana bedrock sill. The accuracy of results and interpretations hinged on precise altitudinal correlation of marker levels between the different boreholes, but the engineering reports and borehole logs each provided a highly accurate datum allowing precise spatial interpolation between the data points. Interpolation accuracy was further controlled and calibrated from 1:50,000 topographic maps, Google Earth spot heights, and handheld GPS measurements in the field, all in good agreement to within 5%. Inspection of sample textures from different core depths also allowed possible confusion between alluvium and in situ weathered rock, and between topsoil and surface landfill, to be lifted or to benefit from altitude corrections.

Peat levels were radiocarbon-dated at two sites, F5 and F6, where excavations during the course of this study could be directly monitored. Radiocarbon age results by Bourgeat and Ratsimbazafy (1975) were also included. The four dated peat samples of excavation site F5 (at depths of –1.80 m, –3 m, –11.60 m, –13.50 m) were also subjected to pollen analysis in order to characterise the vegetation prevalent at the time of peat deposition, infer the palaeoenvironmental conditions, and compare the data with published evidence from other wetlands in Madagascar's Highlands. Pollen samples of 4 g each were collected, prepared following standard chemical treatment (Moore et al., 1991), and each involved a minimum of 300 grain counts. Using a Zeiss microscope at ×400 magnification, pollen taxa were identified from photographic atlases for Madagascar and tropical Africa (Straka, 1991; Schüler and Hemp, 2016; Rasoloarijao et al., 2019).

Mineral characterisation in samples was used to determine sediment provenance, and thus potentially tephra and glass shards from volcanic sources. Mineral extraction was obtained by standard magnetic and density separation methods (Blockley et al., 2005).

In order to test the hypothesis of recent or ongoing basin subsidence, and of possible uplift occurring in the vicinity of the basin's bedrock outlet in the west, a continuous series of seismicity records was acquired from the Institut et Observatoire de Géophysique Appliquée (IOGA) at Antananarivo University. Several thousand seismic events were recorded between July 1988 and October 2017 with their date, time, epicentre latitude and longitude, Richter magnitude, and focal depth. The data series was processed to filter out tremors caused by blasting in the multiple quarries situated within a radius of 10 km around Antananarivo.

Events exceeding M_L 4 were retained as being the most likely to bear upon the long-term morphotectonic behaviour of the Antananarivo Basin.

Lastly, for comparative purposes on a wider scale across the Hautes Terres, we evaluated lavaka density distributions throughout the Ikopa catchment based on aerial photography (Helisoa, 1983; BDPA et al., 1994) and Google Earth updates in order to (i) compare them with documented lavaka densities in catchments around the Alaotra Basin (Mietton et al., 2006), and (ii) assess differences in sediment load entering the two respective tectonic basins. We also cored and radiocarbon-dated sediment fill on the floor of the Ambohibary Basin (Fig. 1; also sometimes referred to as the Sambaina Basin), another semi-enclosed basin of the Highlands (Fig. 2), and compiled previous radiocarbon ages similarly obtained from the Alaotra Basin (Mietton et al., 2018). The preliminary regional dataset thus obtained was conducive to (i) a calculation of long-term sedimentation rates; (ii) the inference of long-term tectonic subsidence rates; and (iii) the possibility to estimate on that basis the opportunities for lake formation in the past and the relative vulnerability of each basin to frequent flooding in the present.

4. Results

4.1. Basin-scale stratigraphy of the Antananarivo plains

Whereas the three auger cores (noted S1, S2, S3, Figs. 6, 7) documented the ubiquity of a shallow peat level at constant depth but provided limited information about deeper levels, the 14 borehole and trench data provided good constraints on the stratigraphy of the sedimentary sequence. The list is as follows: Ivaty-Agrival (F1), Novotel-Ankorondrano (F2), Ibis-Ankorondrano (F3), Tour Orange (F4) Andrahara (F5), Antanimena (F6), Behoririka (F7), Madarail-Soarano (F8), Mahamasina: F9; Anosizato: F10; Tsimbazaza: F11; Bi-Pass (F12), Filatex (F13) and Andoharanofotsy (F14), offset further to the south (Fig. 6). Data obtained by Noizet (1968 a, b) on depths to the bedrock and bedrock lithology along the Ikopa River (e.g. evidence of quartzite outcrops on mid-channel bars) were also mapped, correlated, and triangulated against a series of geodetic markers (Fig. 8).

The altitudinal correlations between cores are remarkably consistent for all levels, including the peat layers (Fig. 7). Overall, the sediment fill is fine-textured and its maximum known thickness does not exceed ~20 m. Peat was found to occur everywhere at one, and at some sites at two, stratigraphic levels (Fig. 7): the shallower level is uniformly widespread across the plain and close to the surface at an altitude of 1248–1250 m; the other typically lies at depths of 10 to 15 m, and thus at altitudes of 1233 m (F3, F4) and 1241 m (F13). This lower peat level was struck by 5 boreholes on the inner plain and along the inner Ikopa floodplain.

Age data for the upper peat layer are summarised in Table 1. The radiocarbon ages were obtained from a single level at Antanimena (F6), and from four different depths at Andrahara (F5), where an organic black clay layer occurs between –11 and –13 m. The near-surface peat deposits are consistently early Holocene (11,270–9100 yr BP), whereas the deeper black clays are late Pleistocene (37,000 yr BP). The absence of deep-seated peat in cores other than F3, F4, F5, F12 and F13 is explained either by the boreholes being insufficiently deep, or because of having struck structural highs of bedrock on the highly irregular, deep weathering mantle of the basin floor (F1, F6, F7, F10).

4.2. Tectonic constraints on the Antananarivo Basin

The cross-section through the Antananarivo Basin (Fig. 9) shows that the sediment fill sequence lies entirely or partly at an elevation below the altitude of the Farahantsana (1248 m) and Bevomanga (1250–1251 m) bedrock sills. The fact that the peat beds have been buried by alluvium (the 'backfill' mentioned in Figure 7 is typically alluvium disturbed by heavy machinery) also testifies to tectonic subsidence. Post-peat sedimentation rates were 0.2–0.3 mm/yr for the near-surface horizon, and 0.3–0.4 mm/yr for the deep peat level at Andrahara, suggesting by inference that subsidence rates have been relatively steady since the late Pleistocene (Table 1). Such geological background rates are plausible for an intraplate setting and, based on recent seismic records, tectonic deformation is ongoing. On an axis from the Ankaratra northward via the Farahantsana–Bevomanga upper knickzone area (Fig. 10), and within a band of just 20 km to the west of Antananarivo, 27 earthquakes ($M_L > 4$) were recorded in the last 20 years (1999–2019), with a M_L 5.08 event on Oct. 20, 2015 (Lat. 18°44.28 S, Long. 47°31.98 E). Widening the band to 70 km towards the west reveals that the region between Antananarivo and Lake Itasy recorded 206 $M_L \geq 4$ earthquakes between 1988 and 2019. Among these, five exceeded M_L 5.0 (maximum of M_L 5.32 on Aug. 23, 1995; 18°.43 S, 46°.24 E; focal depth: 27 km). Although fault-slip and crustal deformation rates are undocumented, a critical seismic alignment striking N–S out of the Ankaratra volcanic edifice thus appears to be a region of active seismicity.

The fracture net and subsidence conspire to control the drainage pattern (Figs. 3, 6). The rivers strike N–S but undergo 90° bends in response to westward tectonic tilting towards the Antananarivo Basin (areas marked 3 and 4 in Fig. 6). At locations numbered 1 to 5 in Fig. 6, the loci of these changes in direction support the notion that E–W faults also control drainage and basin morphology, particularly where they cut across the N–S, quartzite-reinforced basement ridges around Farahantsana and Bevomanga. The fracture pattern also has an influence on right-bank Ikopa tributaries (Mamba, Mambakely, Andranoroasosona; Fig. 6).

4.3. Palaeoenvironmental constraints in the Antananarivo Basin

None among the four Andrahara samples contained tephra, but the sand to silt fraction was rich in all of the primary minerals typical of the gneiss and migmatite bedrock, namely quartz, feldspar and biotite. Numerous smooth oxeas (needle-shaped sponge spicules, with sharp tips at both ends) and belonging to the siliceous skeleton of freshwater sponges (order: Spongillida) were also recovered. Given the additional morphotraits required for identifying encrusting freshwater sponge fauna to genus and species level, these fossil remains are insufficient to be used with confidence as palaeoecological indicators (Pronzato et al., 2017). Nonetheless, specimens of living freshwater sponge species, only recently discovered for the first time in Madagascar (Manconi et al., 2015, 2019), were collected from "silty shallow water along the seasonally flooded riverside" of large rivers similar to the Ikopa, thus providing a plausible clue to late Quaternary floodplain environments in the Antananarivo Basin.

The four samples from the Andrahara (F5) peat deposits were also analysed for their pollen inventories. Pollen preservation and content were generally lower in the two deeper peat samples, but overall pollen analyses revealed substantial differences in terms of pollen assemblages in the four studied peat samples. The pollen spectra at –13.50 m contained Ericaceae (i.e. heather family; 62%), Asteraceae (i.e. daisy family of flowering plants, 14%), and Poaceae (i.e., grasses; 12%). Among the other identified taxa, only Cyperaceae (i.e., sedges), *Podocarpus*, *Artemisia* and *Protea* exceeded proportions of 1%. In the sample at –11.60 m, Ericaceae were still dominant (> 75%). Excepting Poaceae (18%), all the other taxa recorded less than 5%. In the sample at –3 m, Ericaceae (53%) continued to prevail but proportions shifted in favour of Cyperaceae (23%) and Poaceae (19%). Only *Podocarpus* and Asteraceae exceeded 1%. In the shallowest sample at –1.80 m, the pollen spectra were dominated by Cyperaceae (51%) and Poaceae (22%), with a clear eclipse of Ericaceae (down to 10%). In this near-surface peat layer, several taxa such as *Podocarpus*, *Macaranga*, Asteraceae, Urticaceae, Rubiaceae, etc., exceeded proportions of 1%.

The pollen assemblages indicate different paleoenvironmental conditions. With high proportions of Ericaceae (60–80%) associated with high values for Asteraceae, the environmental signature for the deeper organic levels is one of shrubby heathland. By reference to the distribution of modern pollen spectra in central Madagascar (Burney, 1988), such proportions of Ericaceae only appeared during the Last Glacial Maximum at elevations 800–1000 m lower than at present (Straka, 1996). The recorded colder period in the Antananarivo Basin (36–37 ka BP, i.e. one of the cooler stades of Marine Isotope Stage 3, or MIS 3) was thus also drier than today, as likewise confirmed by pollen spectra from the crater lake at Tritrivakely (e.g. Gasse and van Campo, 2001). The shallower samples (–3 m and –1.80 m) document a relative diversification of taxa involving a replacement of heather by sedges and grasses. Whereas sedge supports the notion of a marsh or fen, a proportion of the grasses and other flowering taxa signal seasonally wet meadows in a mosaic also involving woody taxa. The Holocene signature thus illustrates warmer and wetter conditions. Such data are likewise consistent with results from Lake Tritrivakely. The paleoenvironmental conditions of the two generations of peat is strengthened by the fact that both intervals match the early Holocene occurrences dated between 12,000 and 9000 yr BP in the Antsirabe (Burney, 1987, 1996; Burney et al., 2004; Gasse and van Campo, 2001; Razafimahefa et al., 2012) and Alaotra basins (Mietton et al., 2018), and the MIS 3 interval (36,000–32,000 yr BP) in the Ankaratra Massif (Rakotondrazafy, 1992; Straka, 1996; Razafimahefa et al., 2012).

4.4. Basin subsidence rates in Madagascar's Highlands: a comparative analysis

The population of agriculturally important but flood-exposed semi-enclosed basins in the Highlands of Madagascar is much larger (n ≈ 25, e.g. Bied-Charreton et al., 1981) than the examples of the Antananarivo and previously studied Alaotra (Mietton et al., 2018) basins can currently document, but apart from the Antsirabe Basin (Fig. 1; Razafimahefa et al., 2012), few have benefited from coring and stratigraphic analysis. The basins also vary quite substantially in size, although none attain the dimensions of the Alaotra. A few, like the Alaotra and Antananarivo, are entirely in basement, but a large proportion of them were formed by lava dams, particularly around the edges of the Ankaratra and Tsaratanana stratovolcanoes. Neotectonics has often also interfered with the drainage pattern. For example the Mangamila Basin, 70 km NE of Antananarivo (Fig. 1), displays discontinuous vestiges of thick alluvial deposits now perched 40 m above the basin exit point, where the Mananara valley (Figs. 1, 4) continues to down to Anjozorobe (18°31'44.68''S, 47°52'15.70''E). The tectonics-driven drainage capture event detected in that basin could be recent given that a peat sample contained in an alluvial deposit 500 m upstream of the waterfall at the exit point has produced an age of 12.6 ka BP (Table 1). Future research in this and other basins would broaden the scope of these preliminary findings.

The Ambohibary Basin (Figs. 1, 11), which belongs to the class of partly volcanic upland basins, was nonetheless investigated here in order to test the extent to which it could enrich the comparative regional analysis of basin subsidence rates and sharpen the diagnostic criteria required for understanding their vulnerability to flooding. Based on the hypothesis that the outlets of the different basins in the Highlands of Madagascar display a range of sensitivities to environmental change, which should thus impart contrasting environmental behaviours and signatures to each individual case, the following three examples were compared: Ambohibary, Alaotra, and Antananarivo.

4.4.1. The Ambohibary Basin

The Ambohibary Basin, which is nationally important for its fruit and vegetable crops but also for rice (Ambohibary means 'rice village'), is drained by the upper Ilempona River (Fig. 1, 4), which slices through the tectonically active Betampona Fault scarp (Fig. 11). Soil erosion and floods in this mostly volcanic catchment are less pronounced than in the

Antananarivo and Alaotra: no lavaka, limited in-channel sedimentation, few overbank sedimentary deposits on the plain. The exit point is cut in weathered gneiss (Fig. 11), and thereby more vulnerable to river incision than the Farahantsana–Betampona quartzites. Thus facilitated, incision is more likely to keep up with the intermittent shuttering by fault movements at the exit point.

In the absence of sediment cores, tectonic displacement on the fault was estimated from three test pits, in which radiocarbon dating of organic-rich clays could reveal relative basin subsidence. Samples Amb 1 and Amb 3 are from the plain, whereas Amb 2 lies on the edge but 5 m above the modern basin floor (Table 1; Fig. 11). Amb 1 is young (~4 ka BP), whereas Amb 2 and Amb 3 date back to the Last Glacial Maximum, i.e. MIS 2 (~26 ka and ~22 ka BP, respectively). Age–depth ratios for Amb 1 and Amb 3 provide mean sedimentation rates of 0.1 mm/yr in each case, i.e. three times less than at Antananarivo over a similar time span, and one order of magnitude less than the Alaotra Basin. The relative topographic positions of the two samples of similar age, Amb 2 and Amb 3, but with Amb 2 raised by 8 m, suggest a tectonic offset between the two land units (Fig. 11). This interpretation is corroborated by an absence of other vestigial organic layers above the basin floor, thereby ruling out the hypothesis of a palaeolake berm at site Amb 2; and likewise by the regional prominence of the Betampona Fault (Fig. 1). This N–S fault continues south to the Antsirabe Basin, where its recent activity is well documented (Razafimahefa et al., 2012). North of the basin, some > 40 ka lignite beds (Table 1) are also topographically raised (Fig. 11), there also suggesting that postdepositional uplift of organic deposits began in the more distant past.

From a palaeoenvironmental perspective, parts of the basin were intermittently transformed into a wetland during the Lateglacial and Holocene (Lageat and Peyrot, 1974; Samonds et al., 2019), with peat levels, and abundant subfossil remains of aquatic mammals and reptiles. The flagship hippopotamus remains (site Amb 0, Fig. 11), retrieved from a depth of 80 cm and with an age of 14.6 ka BP (17.56 cal BCE; Samonds et al., 2019), also testify to low sedimentation rates (0.05 mm/yr) and, by inference, low subsidence rates. These low rates could accredit at least intermittent conditions suitable for generating a palaeolake, but the floor of the deepest excavation at the centre of the basin (–8 m, Amb 3) did not reveal any lacustrine sediments comparable to those described in detail by Lenoble (1949) in the Antanifotsy Basin, farther to the east (Fig. 11).

4.4.2. The Alaotra Basin

The Alaotra Basin (Fig. 1) is shut off by a raised bedrock sill above a river knickzone (Fig. 4) which, on a 10–10^5-year time scale at least, seems immune to knickpoint retreat (Mietton et al., 2018). Given this boundary condition (Garcia-Castellanos, 2006), the fairly stable long-term surface-area of the lake is ensured by a precarious relative balance between sediment-influx-controlled accommodation space (Mietton et al., 2018) and the tectonic subsidence regime. Sediment delivery is substantial, sedimentation rates are high (0.5–2 mm/yr; Table 1), but these are offset by equally rapid tectonic subsidence rates. Taking advantage of this geodynamic balance, despite some vulnerability to flooding the Alaotra plain has grown to become the most productive rice-growing area of Madagascar. The mean monthly level of the lake varies normally by 2 m between a maximum in March and a minimum in November (Ferry et al., 2009). Levels rise further during tropical cyclones, and rice fields that have been expanded lakeward by farmers to the detriment of natural wetland habitats get flooded. The natural vegetation, some of it woody (amid the 'zetra' papyrus swamps), benefits uniquely from these episodically more extreme floods and is host to a rare endemic species of lemur (*Hapalemur alaotrensis*). An under-reported consequence of rapid subsidence in the Alaotra Basin is a chronic destabilisation of the irrigation infrastructure, which has been precisely engineered and monitored by topometric methods. A subsidence of

1 mm/yr has been seen to offset drainage ditches requiring centimeter-level-precision operational gradients in just 10 years (Mietton et al., 2018). Where subsidence is particularly intense, such as in the parallel Sasomangana and Ilakana valleys (Figs. 1, 12) where the rivers undergo frequent and major avulsions (e.g. documented between 1963 and 1983 by Bourgeon, 1984), new water-filled depressions develop and prove impossible to drain off. Such adverse hydraulic gradients make canal construction and ditching uneconomical in those areas.

4.4.3. The Antananarivo Basin

The Antananarivo Basin is shut off by the hardest rocks in the regional rock strength scale (quartzite), with a presumption of either uptilting (i.e. relatively slower subsidence: 0.2–0.3 mm/yr) (Table 1) of this western edge of the basin floor along an E–W-striking pivot fault, or by dint of an uptilted or upthrown block along the N–S Imerintsiatosika–Antambola seismic line close to the basin outlet (Fig. 10). Sediment aggradation in the last ~40,000 years in the Antananarivo Basin was also a function of river sediment loads. This variable can be estimated from a limited data base summmarised in Table 2. Turbidity measurements obtained from the Mahitsy road bridge (near Farahantsana) at shallow water depths suggest that suspended load in the Ikopa River is moderate: 20 mg/L (for a discharge of 30 m^3/s) to 60 mg/L (128 m^3/s) (EDF, 1950). According to Hervieu (1968), average turbidity varies between 100 mg/L (579 m^3/s) and 930 mg/L (735 m^3/s), but these values were obtained from the Antsatrana gauging station (Fig. 1), i.e. at quite some distance donwstream of the Antananarivo Basin. At Antsatrana, average textural composition of the Ikopa suspended load was 48% clay, 32% silt, 19% fine sand, 1% coarse sand. Based on the mean annual discharge of the Ikopa and a tentative discharge / turbidity rating curve, Roche and Aldegheri (1964) calculated that the mean specific catchment erosion rate was 360 t/km^2/yr.

Despite the sand mining in the active channels of the Ikopa and Sisaony (BDPA et al., 1994), raising of channel beds caused by in-channel sedimentation has clearly been an enduring trend for as long as observations have been available (Douessin, 1974; Ramboarison, 1990). This, however, is the effect of the very low channel gradients on the plain rather than of exacerbated soil erosion in the catchments. Soil loss in the headwaters of the Ikopa is more limited than in other areas of the Highlands because lavaka — which are the only processes capable of delivering coarse bedload to river channels because they expose the lithomarge — are relatively scarce (average catchment-wide density of 0.08 lavaka/km^2, compared for example to the SE area of Lake Alaotra with densities of up to 8/km^2, i.e. 100 times greater) (Mietton et al., 2006). Among the incoming tributaries, the highest lavaka densities are observed in the Sisaony and Andromba subcatchments (locally up to 0.63 lavaka/km^2; see Table 3 and Fig. 10).

Such a relatively low sediment influx combined with the hydrological bottleneck at the basin outlet could in theory promote the existence of at least a shallow lake in the Antananarivo Basin. The absence of a lake is probably explained by the low magnitude of basin subsidence, thus producing a relatively overfilled basin despite the moderate sedimentation rates. Lakes will form typically in underfilled basins (Garcia-Castellanos, 2006), i.e. under conditions closer to what has been evidenced in the Alaotra Basin (Mietton et al., 2018). In Table 2, modelling of basin accommodation space (for sediment, for water) shows that in the Alaotra graben, values of sediment aggradation and tectonic subsidence are relatively balanced (calculated and measured specific denudation rates, respectively abridged as SDRc and SDRm in Table 2, share the same order of magnitude), thus having allowed a very shallow lake (and fen) to persist for ~30,000 years (see also Mietton et al., 2018). Specific denudation in the Sasomangana (2000 t/km^2/yr) and Sahamaloto (2400 t/km^2/yr) catchments (Fig. 1), respectively to the SE and west of Lake Alaotra (Ferry, 1985; Mietton et al., 2006), are thus compensated by the comparatively high subsidence rates that appear endemic to this rift zone of NE Madagascar. The dynamic equilibrium between tectonics and sedimentation at Lake Alaotra is still threatened by mismanagement of the wetland (Mietton et al., 2018), but the more intense tectonic regime than in the Antananarivo setting is what has so far preserved the lake from extinction. In the Alaotra graben, the abundant volumes of sediment delivered are thus absorbed by the accommodation space.

In contrast, despite much lower volumes of sediment delivery, the low tectonic subsidence rate in the Antananarivo Basin is not sufficient to accommodate the sediment influx. This imbalance is expressed in Table 2 by the values of SDRm being much higher than SDRc, indicating that the Antananarivo Basin is vulnerable to overfilling and that there is no potential for a lake. As a result, among the currently documented intermontane basins of Madagascar's Highlands, the wetland plain around the capital city is the most vulnerable to frequent flooding, a situation exacerbated by the previously mentioned risk (see Section 2.1) of levee breaching along the trunk river and its tributaries.

5. Future-proofing the Antananarivo Basin: a discussion on policy perspectives

5.1 A metastable wetland environment since the late Quaternary

The lack of potential for a lake today in the Antananarivo Basin, as inferred from the modelling presented in Table 2, is consistent with the evidence provided by the results that there is also no palaeoenvironmental record of a former lake in the Antananarivo Basin. The lake hypothesis was mooted only by Noizet (1968b) on the basis of right-bank terrace deposits between Bevomanga and Soavinimerina (Fig. 8) — in this case imagined to have formed in the context of a raised lacustrine base level and therefore older than the sediment fill displayed in Figure 7. The occurrence of freshwater sponge remains is likewise inconclusive given that sponges are reported from lotic as well as lentic environments and thus cannot be used as unequivocal evidence for lacustrine conditions. The absence of lacustrine deposits other than perhaps locally and intermittently is a common feature shared by the Antananarivo, Alaotra (Mietton et al., 2018) and Antsirabe intermontane basins (Razafimahefa et al. 2012). As likewise in the Ambohibary Basin (Fig. 1; Lenoble, 1949), alluvial clay and sand in the Antananarivo Basin are the dominant materials. In the Antsirabe Basin, the only distinctive difference is that the fluvio-palustrine sequence is covered by a thick layer of tephra.

In the Antananarivo plains, the sediment has thus buried an irregular topography etched into the weathered crystalline basement, with hills still rising out of the sedimentary sequence and concentrating the rural settlements (as a result, the rice fields are quite a good proxy for mapping the sediment cover by default, at least where urbanisation has not yet encroached; see Fig. 5a for the situation in 2017, and Graphical abstract for 2020). Evidence that the Antananarivo Basin underwent neotectonic activation, perhaps for the first time in the region's geological history, during the Quaternary is indirectly provided by the older peat deposits resting directly on weathered rock profiles such as at sites F3 and F4 (Fig. 7), with fluvio-palustrine sediment aggradation through widespread overbank deposition over the irregular topography of the Antananarivo etch basin beginning around 37,000–36,000 yr BP and continuing uninterrupted until today. Irrespective of its earlier geomorphological history, which currently evades documentation, from at least ~40 ka onwards the Antananarivo Basin thus became a tectonic basin where sediment fill is controlled by a delicate balance between tectonic subsidence rate and hydrological outflow at the outlet. The nature of sedimentation dynamics was apparently a direct function of the rate of tectonic forcing, with peat deposition apparently coinciding with accelerations in tectonic subsidence (Table 1).

5.2. Flood-mitigating options for Antananarivo's upland plain

The flood hazard in the Antananarivo and Alaotra basins poses major problems for agriculture and human settlement, but it is clearly around the capital city, where a population of 700,000 already lives in the flood zone, that environmental issues are most acute. Catastrophic flooding events, often unreported in the global media but occurring with increasing frequency (March 1982, Feb. 1994, Jan. 2007, Feb. 2015, Feb. 2019, Jan. 2020), are the result of low-grade housing, mostly populated by the more recently arrived among the urban poor, sprawling across the lowest-lying areas of the city (Fig. 5b). Under the pressures of urbanisation, by 2004 agricultural land use had fallen to 43% of the plain area. By 2010, irrigated crops had fallen to 2530 ha (6800 tenancies), the remainder lost to urban conversions (M.S. Andrianjafimahatratra, President of the Water Users' Federation, pers. comm. 2019). Raising the agricultural plain for urban construction through landfill operations was previously widespread north of the Ikopa, but it has now expanded to the left-bank areas, mainly upstream of Tanjombato (Fig. 5a). The consequences of urbanisation on wetlands are well known, and involve (i) sanitation hazards relating to stagnant water, to its pollution, and to unsuitable or inexistent sewage infrastructure — in both cases exacerbated in Madagascar by the coincidence between the rainiest and warmest seasons; and (ii) safety hazards (structural failure of buildings, electrocution, impeded traffic). Given these threats and constraints, any land-use and urban planning project for the capital city is narrowly linked to hydrological management of the Ikopa's channel and floodplain, particularly downstream of the city centre. The floods of Feb.–March 2015, exacerbated by cyclone Chezda, entailed the displacement of 30,000 residents for several months, caused several dozen fatalities (Defrise, 2020), and came as a shock to political authorities clearly oblivious to the 1959 and earlier catastrophic events.

5.2.1. The playbook of hydraulic engineering solutions

The behaviour of each tectonic basin's hydrological outlet is key to the delicate balance under which the intermontane wetland can avoid extinction, and under which it can sustain its function as provider of (i) supporting ecosystem services to agriculture in a mountainous nation, and of (ii) provisioning ecosystem services to its sprawling capital city in the form of flood-hazard mitigation.

Intuitive awareness of the importance of this boundary condition has motivated hydraulic and agricultural land management authorities to seek engineering solutions such as bedrock channel deepening at Farahantsana during the first half of the 20th century, described in Section 2.1. Similar designs were likewise planned at the outlet of the Ambohibary Basin on the upper Ilempona River during the 1940s; and at Lake Alaotra, where, in a classic situation of destocking post-wartime surpluses of explosives, Longuefosse (1923) advocated an expensive project involving 200,000 m^3 of bedrock blasting of the Alaotra lake outlet (Maningory knickpoint, Fig. 4). The objective was to drain away the lake water, reclaim vast expanses of wetland as a result, and regulate outflow with a 14-m-high, 17,000 m^3 concrete dam equipped with a hydroelectric power station. By pumping water to convey it along new canals to parts of the Alaotra Basin until then impossible to develop just by gravitational irrigation (Ciolina, 1946), rice cultivation would thus expand and prosper.

All of these engineering initiatives were soon abandoned because of their prohibitive costs, and because of their ensuing negative ecological and engineering impacts: headward erosion of the exit gorge into the basin in the first two cases; lowering of groundwater tables as a result of channel incision, causing a drop in water levels in wells on the floodplain and impacting the parameters of rice cultivation; and permanent flooding of arable lands on the lakeshore because of a widespread backwater effect at Lake Alaotra. The Alaotra fenland, home to some endemic wildlife species, is now protected by the Ramsar Convention (since 2003).

Blueprints for a number of new projects aimed at regulating the Ikopa River and managing land use on the floodplain have been drafted by environmental engineering consultancies (Someah, 2010; Someah–Artelia Madagascar, 2012; BRL Ingéniérie, 2017a, b). One masterplan advocates the construction of a left-bank canal parallel to the Ikopa; a variant envisages that this artificial overflow structure should be activated as a derivation canal with a succession of spillways in operation only during floods. This would maintain the current functions of the river's natural channel, including during the low flow season. Reinforced weir structures designed to arrest headward channel erosion have been planned for the Ikopa and the Mamba rivers. However, like their colonial ancestors, because of the expropriations, land acquisitions and the magnitude of earth-moving operations involved, all of these projects are exceedingly expensive. Additionally, flood hazard simulations have been restricted to return periods (and peak flood discharges) of 5 (210 m^3/s) to 10 years (420 m^3/s). This amounts to lowering the Ikopa water line by 2 m and 1.3 m (for the 5- and 10-year return periods), respectively. Given the strong likelihood of much higher discharges in the future (e.g. 100-year flood), these hard-defence solutions would imply rapidly increasing costs for every additional increment of engineered waterline lowering (e.g. for accommodating the 20-, 50-year floods and above). Accordingly, and given that the lower-frequency, higher-magnitude floods are the most damaging, the cheaper, yet still expensive, options are already almost pointless. Undoubtedly, a magnitude of flood waterline lowering by just 2 m on the Ikopa would be beneficial as it would enhance gravity-driven drainage gradients for both agricultural and urban (sewage etc.) infrastructure. Nonetheless, the impact from larger floods (likely and perhaps increasingly frequent in the future given the accelerating trend since 2015) is currently undocumented. Its consequences for water table levels across the plain, for example, is unknown because the interaction between the river and the floodplain aquifers is still poorly understood (note that the new 28 MW hydroelectric power station at Farahantsana, soon to be completed at the time of writing, is a penstock-fed, run-of-the-river facility without a dam across the Ikopa channel, and should thus have no influence, such as backwater effects, on matters addressed in this study).

Continuing unregulated urban growth of Antananarivo's metropolitan area strongly suggests that ribbon development along future road arteries will also alter rainfall–runoff response times, worsen stormwater containment and first-foul flushes, and lengthen floodwater recession times back to the river and water table. Available funds should thus prioritise the protection of the agricultural plain north and east of the Ikopa channel and preserve water-spreading buffer zones already present in those areas. Enforcement of this policy should be uncompromising in the face of pressure from property developers.

5.2.2. Integrated watershed management options

Solutions to urban flooding and crop destruction in the upland plains of Madagascar may require proximal engineering fixes, but also depend on an understanding of the total environment at the entire catchment scale. This includes land-use patterns and agricultural practices, which impact on water and sediment delivery further downstream. Here we examine land cover solutions as a means of curbing peak discharges and in-channel alluvial aggradation, which both threaten the levees, the plains, and thus the sustainability of the nation's agriculture and the safety of city dwellers. These issues are most serious in the two upland ricebowls of Madagascar: Antananarivo and the Alaotra, because in other agricultural basins such as Ambohibary and Antsirabe, hillslopes in the young and moderately weathered volcanic rock are not gullied by lavaka and release more limited masses of debris. Furthermore, those basins are situated at higher altitudes, and focus on crops more resistant to winter temperatures (commonly falling to below 4 °C) than rice. Resource optimisation is thus less narrowly dependent on the subtle strategies required in paddy cultivation for controlling water budgets at nested time scales, including at short notice.

Natural soil erosion is endemic in the Ferralsols of the Alaotra catchment area, and erosion-control and slope restoration measures such as gabions and brushwood check dams have been deployed in vain for many years. In the Ikopa catchment, which is endowed with far fewer lavaka and where conditions are thus more favourable to ecological engineering, the smaller number of active lavaka (most in the Andromba and Sisaony subcatchments, Fig. 10) has been fairly successfully curbed by afforestation of the erosional scars with *Eucalyptus robusta*, *Grevillea banksia*, *Cassia spectabilis,* and seeding of herbaceous plants such as *Crotalaria*, particularly *Crotalaria juncea* (sunn hemp): a fast-growing, nitrogen-fixing, nematode- and drought-resistant legume forming dense cover as well as a source of green manure, fodder, and perhaps biofuel in the near future. Whereas the Alaotra plain is thus potentially more vulnerable to sediment aggradation than its Antananarivo counterpart because lavaka densities are up to 100 times greater, the Antananarivo plain nonetheless lacks the Alaotra's vast foreshore area, and thus the capacity to contain floodwater and sediment upstream of Antananarivo's urban and irrigation infrastructure. This contrast between the two settings highlights a situation where the potential for disconnectivities in the sediment cascade (Fryirs, 2013) is much greater in the Alaotra than in the Antananarivo basins (Fig. 12). The capital city is thus uniquely exposed (Fig. 5).

Land use characteristics in the Ikopa and Alaotra catchments are relatively similar, but disconnectivities in the sediment cascade matter at all scales within the catchment area, and in the case of the Antananarivo Basin, upscaling this concern for sedimentary disconnectivities to the entire catchment is where the key to future policy action lies. Population densities are low and intensive agriculture is restricted to valley bottoms (rice), which are wide in the Alaotra area and narrower in the Ikopa catchment, and to terraced interfluve footslopes on

Ferralsols and colluvium. The networks of flat-floored valleys (dambos) constitute the first sediment trap, or disconnectivity node, in the catchment-scale sediment cascade. As loci of sediment aggradation in quantities that remain manageable on an annual basis, unmechanized farming communities have evolved a number of strategies for retaining the sediment and coopting it to agricultural benefit. The antler-shaped networks of valley floors (examples visible in Figure 5a), however, only represent ~10% of the land area. The remaining 90% of the Ikopa catchment (and no less than ~50% nationwide; Randrianjafy, 2006) consist of low-gradient interfluves with convex hillslopes underlain by 10–30-m-thick weathering profiles and named 'tanety'. The 'tanety' are potentially far more vulnerable to runoff-related erosion and gullying, and deserve greater attention.

The elevation band of steep lower hillslope convexities is where village settlements occur. It is usually well tended to by terracing and various forms of polyculture, and well managed by indigenous soil conservation methods involving terracing and grassy strips on arable field boundaries (Roose, 1982). The land use higher up on hillsides and hilltops today is commonly plantation forestry (eucalyptus, pine) in replacement of grassland savanna, mainly for urban charcoal manufacturing and timber consumption. This woodland cover increases evapotranspiration and infiltration but, whether under state-controlled or corporate land use, it is also resented by cattle herders, who for centuries have been traditionally co-opting hilltops for grazing under complex customary rules also involving fire management practices. The cross-country transhumance routes are well known (Raison, 1969), and herds of many tens of thousands of zebu gravitate annually to the Antananarivo area, where some of the country's largest cattle markets and industrial abattoirs are located. The competition between state or private forestry and traditional pastoralism is enhanced, in areas closer to the cities, by recent land grabs by urban elites or foreign investors with alternative land development objectives. Whether under a 'kijàna' regime (cattle pasture and rest area managed locally for the village herds), or the ‘tanin’aômby’ regime, where large herds of transhumant zebu cattle are left to roam freely (Rasamoelina, 2017), the grassland surfaces under customary common-property management are shrinking, thus increasing risk of overstocking and overgrazing. The potential for enhancing surface runoff and soil erosion on the ‘tanety’ as a result of inadequate rangeland management is therefore substantial (Fig. 12).

A watershed and irrigated-zone management policy was formulated for Madagascar at the turn of the 21st century. As in many developing countries, in a political context where environmental policies are based on close relationships between governments, global environmental NGOs, and development banks, the governance of natural resources in Madagascar draws farmers and other land managers into partnerships with global public–private networks (Duffy, 2006). As a result, land management solutions deployed in Madagascar are imbued with often quite specific corporate doctrines, most of them crafted by overseas development agencies and consultancies. This affects the politics of environmental aid to Madagascar, and likewise the rhetoric in which it is embedded (Corson, 2016).

Most funding bodies in Madagascar’s agricultural sector, which usually broaden their scope to rural development and watershed management (Agence Française de Développment, Japan International Cooperation Agency, World Bank, Kreditanstalt, USAid, Food and Agricultural Organization of the UN etc.), have thus become major partners of the new PNBV/PI (Programme National Bassins Versants Périmètres Irrigués) launched by the central government in 2006. This policy is based in theory on a catchment-wide approach to land-use and land-cover management, with consideration for up- as well as downstream environments, and on a diverse range of action plans and self-governing organisations partly modeled on the chambers of agriculture prevalent in some European countries. These are aimed at strengthening farmers’ governance structures (federations, social networks, training workshops…) and placing agricultural producers centre-stage. The main three strategies of 'agro-ecological' engineering in that context each apply to different facets of the landscape system. They are usually sponsored by foreign NGOs and funding agencies (Serpantié et al., 2013) and comprise of: (i) payment for watershed-based environmental services (e.g. Porras et al., 2008) — more often, however, in steep forest areas than in wetlands or agricultural watersheds (Wendland et al., 2010; Villa et al., 2015; Onofri et al., 2017; Van Soesbergen and Mulligan, 2018); (ii) rainfed 'conservation agriculture' on the hilltops, using a package of techniques usually imported from Brazil (Knowler and Bradshaw, 2007; Serpantié, 2009); and (iii) a system of rice intensification (SRI) aimed at dambos and intermontane basins, developed by an NGO from Madagascar with attempts to export it to the rest of world (e.g. Serpantié, 2017).

A difficulty with applied research in agronomy is that sources of information about its results are rarely independent from the various organisations and agencies self-promoting their own experiments and innovations (Serpantié et al., 2013). Here we merely emphasize that despite the rich forms of development-motivated advocacy underpinning the PNBV/PI, and despite the fact that the grassland-covered 'tanety' constitute up to 90% of the land surface in any given part of the fluvial catchments (Fig. 12), pastoralists, who are socially marginalised in Malagasy society, are often invisible to the development agencies and virtually never integrated into those policies. The aid policies target sedentary village communities and focus on elaborating legislative frameworks aimed at enshrining land-tenure security for producers and farmers. The pastoralists nonetheless impact on the territory through their cyclical combination of hilltop grazing and forage burning. The grassland communities are dominated by *Aristida*, *Loudetia, Ctenium*, *Andropogon*, *Panicum*, *Imperata*, all of which have Malagasy vernacular names (Sarremejean, 1961; Bourgeat et al., 1995), and are unpalatable to zebu unless burned periodically to promote new flushes (Granier et al., 1976). They are, however, too tussocky and shallow-rooted to avoid soil erosion under conditions of overstocking (Fig. 12).

Two categories of pastoralists are concerned by the prospect of sustainable grassland management: (i) the village communities themselves, who practice mixed farming and thus usually have a small village herd of mainly male zebu (used as draught cattle), which is kept on the interfluves away from dambo crops during the rice-growing season; and (ii) transhumant pastoralists, who travel long distances, e.g. from the highlands west of Lake Alaotra across to the east coast (Toamasina), and from the savannas and pseudo-steppes of the western scarplands (Fig. 1) eastward to the Ikopa catchment and Antananarivo's abattoirs. The nomadic pastoralists are not present all year but drive very large herds of bovine cattle over the rangelands towards the end of the dry season (also the cooler season), keeping to these upland droveways as a means of avoiding arable fields in the dambos and conflict with farmers. The timing of this mass movement occurs for economic reasons, i.e. (i) the need to sell the cattle at a time when other forms of revenue (e.g. crops) are scarce, (ii) the low dividends from continuing to graze cattle on dry pasture, and (iii) the opportunity of selling or slaughtering the cattle before seasonal decline in weight loss. Crucially, however, these late dry-season livestock loads on thin, tussocky pasture also imply that the first rains have a disproportionately large impact on the soils and hydrology of the savanna-covered interfluves, and therefore also have consequences for surface runoff and sediment load among the rivers converging on the Antananarivo Basin. These impacts are exacerbated by fire practices. Burning enhances the beneficial 'green bite' appreciated by the cattle, but is also tacitly appreciated by farmers because (i) the runoff on the 'tanety' routinely conveys fertile ash to the arable dambo soils, and (ii) the rice farmers are also the owners of part of the livestock using the interfluves under the kijàna regime. Most rural stakeholders thus have a vested interest in fire and pastoralism, but collectively conspiring, overall, to far-field hydrological hazards downstream.

At catchment scale, a recommended agro-ecological strategy to save intermontane basin wetlands such as the Alaotra and Antananarivo from excessive sediment aggradation and/or to buffer the catchments against catastrophic flooding would thus be to expand the introduction of new pasture and forage plants — whether grasses or legumes — to the naturally treeless interfluve hillslopes and hilltops. The nitrogen-fixing *Stylosanthes* (pencilflower; Fabaceae), native to the Americas and the world's most widely used pasture legume (Granier et al., 1972; particularly *Stylosanthes guianensis*: Cook et al., 2005; Husson et al., 2008); and most of all *Brachiaria* (Poaeceae), native to central Africa, have been recommended (Granier et al., 1966; Bosser, 1969; Seguy, 2006). *Brachiaria brizantha* (bread grass, a tufted perennial which stays green even during dry seasons of 3 to 6 months) has deep roots (up to 2 m) and thus stabilises the soil. It is recommended over *Brachiaria ruziziensis* (Congo grass, which has also been introduced to Madagascar) because of its better natural seed dispersal capacity, wider ecological niche (rainfall, temperature, pH, etc.), and tolerance to low-fertility soils even though it improves with manuring. It can also be used as cut-and-carry hay and silage for village cattle (Cook et al., 2005). Used in combination, these multi-purpose grasses and creeping legumes can withstand high stocking rates in areas currently identifed as vulnerable to soil erosion (e.g. Fig. 12); are adapted to the nutrient-poor, low pH soils; and combine the benefits of palatability to bovine cattle, of fire and drought resistance (large soil seed bank of the pencilflower, and thus rapid recovery), with good runoff-arrest and soil-retainment abilities (Ferry et al., 2009, 2013). They are also advocated as a substitute to the endemic use of fire (Randrianjafy, 2006), with obvious value for curbing carbon emissions.

Although introduced to Madagascar in the 1950s, however, *Brachiaria* has never been at the forefront of development policies. Additionally, fire practices in Madagascar are widespread but culturally and politically complex (Kull and Laris, 2009). As a result, any prospects of pastoralism without fire would probably need to adjust rangeland management practices to the introduction of new forage plants on multiple institutional and behavioural levels. One of the social bottlenecks could be resistance from dambo farmers to see any change to fire practices on the 'tanety' because they also benefit indirectly from the ash-laden runoff. Nevertheless, forging an alliance with pastoralists in ways that enhance their livelihoods and preserve their rangeland resources is recommended here as a way forward, thus establishing a counter-intuitive feedback loop between tectonic regime and rangeland management for the purpose of preserving the sustainability of rice farming — especially in the Alaotra Basin — and mitigating flood hazards in and around the nation's capital city: a potential win–win for town and country, upland and lowland.

5.2.3. Overarching policy perspectives and wider methodological implications

While attempting to assess the assets and vulnerabilities of the Ganga–Brahmaputra delta in Bangladesh as a safe operating space, Hossain et al. (2017) showed that operating the life-supporting system of the floodplain to increase long-term resilience, and to help to revise environmental policies which were having negative impacts on a regional scale, required managing feedback on several levels, including the slow biophysical variables. In central Madagascar, we have shown that a key slow variable was the tectonic regime; another, equally subtle key was the vulnerability of the Ferralsols to topsoil erosion, exacerbated runoff, and possible lavaka initiation (Fig. 12). That window of vulnerability is opened every year as a consequence of overstocking on interfluves and lighting bush fires at the end of the dry season. This regional study focusing on the rice-growing tectonic basins of Madagascar thus demonstrates how the concepts of slow and fast variables, shocks (e.g. Walker et al., 2012), tipping points, limits to adaptation, and boundaries for sustainable development may be defined in real-world socio-ecological systems.

Like everywhere else in the world, deforestation, land degradation and urbanisation in watersheds increase the speed at which water runs off the land and into rivers, and climate change may be increasing the variability, intensity and frequency of cyclones and other severe rainstorms. The construction of hard defences such as artificial levees and embankments, however, creates a false sense of security and encourages urban developers and speculators to open-up the floodplain for settlement. This makes future floods more damaging than if the plain had been left undeveloped. Furthermore, expensive structural controls such as dams and levees can worsen the severity of extreme floods because the river level becomes raised above the height of the surrounding plain, with potential for disastrous flash floods when the levees break. A recurring tendency among human societies is to underprepare for disasters because of environmental myopia, historical amnesia, administrative inertia, technological optimism, herding bias (a tendency to base choices only on the observed actions of others), and/or — as emphasised in this study — simplification bias: i.e. a tendency to selectively attend to only a subset of the relevant factors requiring to be considered when making choices involving risk (Meyer and Kunreuther, 2017). Awareness of these biases, and cultivating the memory of such historically documented past disasters along the Ikopa River, is essential for planning the future of the Madagascar's upland economy. The promotion of watershed-based environmental services in Madagascar would gain from not just focusing, for example, on the prevention of siltation of hydroelectric dam infrastructures in the forest belt of the Highlands (Villa et al., 2015), but also from extending as much as possible the sustainability of the intermontane grainbaskets of the country, which are located in a savanna / pseudo-steppe environment. This involves not just intensifying the agriculture through agronomic and hydraulic engineering on the plains themselves, which has long been the major focus of research and funding efforts, but also an integrated consideration for subsistence agriculture and pastoralism in the upper watersheds, concern for river knickpoint dynamics driven by active tectonics, and a strict and uncompromising control of land use and urban planning around the sprawling capital city. All are intimately linked through sediment budgets in the catchment-wide sediment cascade.

6. Conclusion

The water and sediment budgets of the intermontane basins in Madagascar's Highlands are strongly dependent on the metastable equilibrium of the land-use mosaics in the catchments. With the added basin-outlet control by tectonics, basin-floor subsidence rates, river channel dynamics at the basin exit points, and the urban sprawl of the capital city across its floodplain, the Antananarivo Basin is increasingly exposed to damaging flood risks as a result of ill-conceived engineering fixes and unregulated urbanisation. Having been functioning as a dynamic natural wetland since at least the late Pleistocene, this environment is unlikely to yield easily to continuing reclamation efforts beyond certain limits. The fact that rural and urban development schemes in Madagascar both persistently ignore the socially most vulnerable, i.e. respectively pastoralists and the urban poor, confirms that there is a strong political component to the environmental issues at stake. As also shown here in the Highlands of Madagascar, embracing the total environment not only means understanding how the different 'spheres' (atmo-, hydro-, litho-, bio-, anthropo-) intersect and interact through cumulative causation, offsets, feedbacks or nonlinearities, but also how systems scale up or down according to nested or cascading architectures. It also benefits from integrating social and biophysical records at regional scales through time by taking a long view of the past through historical records (e.g. Dearing et al., 2015; Shanmugasundaram et al., 2018) and by dating sedimentary archives, thereby providing policy recommendations that are calibrated not just on treating the symptoms and — often ineffectually — controlling the fast variables (e.g. lavaka scarring, episodic levee breaching), but also calibrated on an understanding of the underpinning slow variables — i.e. those that no one can control (tectonic regime, cyclones, intrinsically low soil fertility and vulnerability to runoff erosion), but where an awareness of their existence adjusts the bandwidth of what it possible or relevant, and sets the dial of policy framing efforts to a position where long-term sustainable solutions are realistic, ecological, cost-effective, and socially just.

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References cited

Abé, Y., 1984. Le riz et la riziculture à Madagascar. CNRS Editions, Paris, 232 p.

Aldegheri, M., 1964. Monographie hydrologique de l'Ikopa et de la Betsiboka. ORSTOM. Facteurs conditionnels du régime. Vol. 1 (Facteurs géographiques), 63 p.; vol. 2 (Facteurs climatologiques), 91 p.

Andriamampianina, N., 1985. Les lavaka malgaches : leur dynamique érosive et leur stabilisation. Rev. Géogr. Madag. 46, 69–85.

Andriampenomanana, F., Nyblade, A.A., Wysession, M.E., Durrheim, R.J., Tilmann, F., Julià, J., Pratt, M.J., Rambolamanana, G., Aleqabi, G., Shore, P.J., Rakotondraibe, T., 2017. The structure of the crust and uppermost mantle beneath Madagascar. Geophys. J. Int. 210, 1525–1544, doi.org/10.1093/gji/ggx243.

Anonymous, 1965. Note hydrologique sur les rivières des hauts plateaux de Madagascar. Chapter 5, pp. 38–57.

Arthaud, F., Grillot, J.C., Raunet, M., 1990. La tectonique cassante à Madagascar : son incidence sur la géomorphologie et sur les écoulements. Can. J. Earth Sci. 27, 1394–1407, doi.org/10.1139/e90-149.

Aryal K., Thapa, P.S., Lamichhane, D., 2019. Revisiting agroforestry for building climate resilient communities: a case of package-based integrated agroforestry practices in Nepal. Emerg. Sci. J. 303–311, dx.doi.org/10.28991/esj-2019-01193.

Attoumani, A., Victor, R., Randriamampandry, C., Andrianirina, R., 2019. La croissance de la ville d'Antananarivo et ses conséquences. Madamines 1, 25 p.

BDPA (Bureau pour le Développement de la Production Agricoles d'Outre-Mer), SCETAGRI, GERSAR BRL, EEP DINIKA, 1994. Etude d'aménagement du bassin versant de l'Ikopa dominant la plaine d'Antananarivo ; gestion de la filière sable : rivières Ikopa, Sisaony et Mamba dans la traversée des plaines d'Antananarivo. Internal report, 79 p., with three 1/100,000 scale maps.

Aubry, C., Ramamonjisoa, J., Dabat, M.H., Rakotoarisoa, J., Rakotondraibe, J., Rabeharisoa, L., 2012. Urban agriculture and land use in cities: An approach with the multi-functionality and sustainability concepts in the case of Antananarivo (Madagascar). Land Use Policy 29, 429–439, doi.org/10.1016/j.landusepol.2011.08.009.

Barimalala, R., Rambolamanana, G., 2008. Solutions de certains mécanismes au foyer dans la partie centrale de Madagascar. Mada-Géo 12, 2–6.

Bied-Charreton, M., Bonvallot, J., Dandoy, G., Delenne, M., Hugot, B., Peltre, P., Pomart, E., Portais, M., Raison, J.P., Randrianarisoa, J., 1981. Cartes des conditions géographiques de la mise en valeur agricole de Madagascar. ORSTOM, Paris, 187 p.

Blockley, S.P.E., Pyne-O'Donnell, S.D.F., Lowe, J.J., Matthews, I.P., Stone, A., Pollard, A.M., Turney, C.S.M., Molyneux, E.G., 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. Quat. Sci. Rev. 24, 1952–1960, doi.org/10.1016/j.quascirev.2004.12.008.

Bosser, J., 1969. Graminées des pâturages et des cultures. Mémoire ORSTOM 35. ORSTOM, Paris, 440 p.

Bourgeat, F., 1968. Carte pédologique, Tananarive, 1:100,000 scale. ORSTOM, Tananarive, 60 p.

Bourgeat, F., Petit, M., 1969. Contribution à l'étude des surfaces d'aplanissement sur les Hautes Terres centrales de Madagascar. Ann. Géogr. 426, 158–188, doi.org/10.3406/geo.1969.15837.

Bourgeat, F., Ratsimbazafy, C., 1975. Retouches à la chronologie du Quaternaire continental de Madagascar ; conséquences sur la pédogenèse. Bull. Soc. Géol. Fr. 17, 554–561, doi.org/10.2113/gssgfbull.S7-XVII.4.554.

Bourgeat, F., Randriamboavonjy, J.C., Sourdat, M., 1995. Les unités morphopédologiques à Madagascar, potentialités et contraintes régionales. Akon-ny Ala 17, 40–49.

Bourgeon, G., 1984. Région du Lac Alaotra, Madagascar. Etudes pédologiques de quelques plaines périphériques, échelle 1/20 000. IRAT, Montpellier, 101 p.

Brenon, P., 1952. La plaine de Tananarive et les possibilités d'abaissement du niveau de l'Ikopa. Bureau géologique, Antananarivo, 9 p.

BRL Ingéniérie (Compagnie d'Aménagement du Bas-Rhône et du Languedoc), 2017a. Mission de maîtrise d'œuvre pour le programme intégré d'assainissement d'Antananarivo. Tranche ferme. Rapport final de l'activité 1, 127 p.

BRL Ingéniérie (Compagnie d'Aménagement du Bas-Rhône et du Languedoc), 2017b. Mission de maîtrise d'œuvre pour le programme intégré d'assainissement d'Antananarivo. Tranche ferme. Rapport final de l'activité 3, 116 p.

BRL Ingéniérie (Compagnie d'Aménagement du Bas-Rhône et du Languedoc), 2018. Digues des rives gauches et droites de l'Ikopa et du canal C3. Aménagements de berge du canal C3. Vol. 1, 24 p.

Burney, D.A., 1987. Pre-settlement vegetation changes at Lake Tritrivakely, Madagascar. Paleoecol. Afr. 18, 357–381, doi.org/10.1016/0031-0182(88)90081-8.

Burney, D.A., 1988. Modern pollen spectra from Madagascar. Palaeogeogr. Palaeoclimatol. Palaeoecol. 66, 63–75, doi.org/10.1016/0031-0182(88)90081-8.

Burney, D.A., 1996. Climate change and fire ecology as factors. In: Lourenço, W.R. (Ed.), Biogéographie de Madagascar. ORSTOM Ed., Paris, pp. 49–58.

Burney, D.A., Burney, L.P., Godfrey, L.R., Jungers, W.L., Goodman, S., Wright, H.T., Jull, A.J.T., 2004. A chronology for late prehistoric Madagascar. J. Hum. Evol. 47, 25–63, doi.org/10.1016/j.jhevol.2004.05.005.

Campbell, G., 2005. An economic history of imperial Madagascar, 1750–1895: the rise and fall of an island empire. Cambridge Univ. Press.

Chaperon, P., Danloux, J., Ferry, L., 1993. Fleuves et rivières de Madagascar. ORSTOM Editions, Paris, 874 p.

Ciampalini, A., Frodella, W., Margottini, C., Casagli, N., 2019. Rapid assessment of geo-hydrological hazards in Antananarivo (Madagascar) historical centre for damage

prevention. Geomat. Nat. Haz. Risk 10, 1102–1124, doi.org/10.1080/19475705.2018.1564375.
Ciolina, F., 1946. Hydraulique agricole et riziculture à Madagascar. Rev. Int. Bot. Appl. Agricult. Trop. 26, 405–422.
Cook, B.G., Pengelly, B.C., Brown, S.D., Donnelly, J.L., Eagles, D.A., Franco, M.A., Hanson, J., Mullen, B.F., Partridge, I.J., Peters, M., Schultze-Kraft, R., 2005. Tropical forages: an interactive selection tool. CSIRO, DPI&F (Queensland), CIAT, and ILRI, Brisbane, Australia.
Corson, C.A., 2016. Corridors of power: the politics of environmental aid to Madagascar. Yale University Press, New Haven, 305 p.
Cox, R., Zenther, D.B., Rakotondrazafy, A.F.M., Rasoazanamparany, C.F., 2010. Shakedown in Madagascar: occurrence of lavaka (erosional gullies) associated with seismic activity. Geology 38, 179–182, doi.org/10.1130/G30670.1.
Dabat, M.H., Razafimandimby, S., Bouteau, B., 2004. Atouts et perspectives de la riziculture périurbaine à Antananarivo (Madagascar). Cah. Agric. 13, 99–109.
Daily, G.C., Ellison, K., 2002. The new economy of nature: how to make conservation profitable. Island Press, Washington D.C., p. 61–85.
Dearing, J.A., Wang R., Zhang K., Dyke J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton T.M., Raworth, K., Brown, S., Carstensen, J., Cole, M.J., Cornell, S.E., Dawson, T.P., Doncaster, C.P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A.W., Nykvist B., Poppy G.M., 2014. Safe and just operating spaces for regional social-ecological systems. Glob. Environ. Chang. 28, 227–238, doi.org/10.1016/j.gloenvcha.2014.06.012.
Dearing, J.A., Acma, B., Bub S., Chambers, F., Chen, X., Cooper, J., Crook, D., Dong, X., Dotterweich, M., Edwards M., Foster, T., Gaillard, M.J., Galop, D., Gell, P., Gil, A., Jeffers, E., Jones, R., Krishnamurthy, A., Langdon, P., Marchant, R., Mazier, F., McLean

C., Nunes, L., Raman, S., Suryaprakash, I., Umer, M., Yang X., Wang, R., Zhang, K., 2015. Social-ecological systems in the Anthropocene: the need for integrating social and biophysical records at regional scales. Anthropocene Rev. 2, 220–246, doi.org/10.1177/2053019615579128.

Defrise, L., 2020. Terres agricoles face à la ville : logiques et pratiques des agriculteurs dans le maintien des espaces agricoles à Antananarivo, Madagascar. Unpubl. PhD thesis, AgroParisTech, Paris, 351 p.

Delaunay, A., 2018. Les mouvements verticaux de Madagascar (90–0 Ma) : une analyse couplée des formes du relief et de l'enregistrement sédimentaire des marges ouest malgaches. Unpublished PhD thesis, Université de Rennes 1, 374 p.

Delubac, G., Rakotoarison, W., Rantoanina, M., 1963. Etude géologique et prospection des feuilles Tananarive–Manjakandriana à Madagascar au 1/100 000 (3 maps). Travaux du Bureau Géologique n° 114, Antananarivo, 49 p.

De Martonne, E.-G., 1911. La densité de population à Madagascar. Ann. Géogr. 109, 77–85, doi.org/10.3406/geo.1911.7490.

Douessin, R., 1974. Géographie agraire des plaines de Tananarive. Rev. Géogr. Madag. 25, 9–156.

Duffy, R., 2006. Non-governmental organisations and governance states: the impact of transnational environmental management networks in Madagascar. Env. Polit. 15, 731–749, doi.org/10.1080/09644010600937173.

Dupuy, S., Defrise, L., Lebourgeois, V., Gaetano, R., Burnod, P., Tonneau, J.-P., 2020. Analyzing urban agriculture's contribution to a southern city's resilience through land Cover mapping: the case of Antananarivo, capital of Madagascar. Rem. Sens. 12, 1962, doi.org/10.3390/rs12121962.

Dussarat, B., 1994. Structure et fonctionnement des aquifères de socle altéré en zone tropicale d'altitude : cas du bassin de Mahitsy (Hautes Terres de Madagascar). Unpublished PhD thesis, Université de Montpellier 2, 171 p.

Electricité de France (EDF), 1950. Monographie hydrologique du bassin supérieur de l'Ikopa, 152 p.

Ferry, L., 1985. Etude bathymétrique de la retenue de Sahamaloto. ORSTOM, Antananarivo, 6 p.

Ferry, L., Mietton, M., Robison L., Erismann, J., 2009. Le lac Alaotra à Madagascar. Passé, présent et futur. Z. Geomorph. 53, 299–318, doi.org/10.1127/0372-8854/2009/0053-0299.

Ferry, L., Mietton, M., Touchart, L., Hamerlynck, O., 2013. Lake Alaotra is about no disappear. Hydrological and sediment dynamics of an environmentally and socio-economically vital wetland. Dyn. Environ. (Bordeaux) 32, 105–119.

Fourno, J.P., 1990. Sismicité du centre de Madagascar. C. R. Acad. Sci. Paris, Série II, 310, 377–383.

Fryirs, K., 2013. (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Proc. Land. 38, 30–46, doi.org/10.1002/esp.3242.

Garcia-Castellanos, D., 2006. Long-term evolution of tectonic lakes: climatic controls on the development of internally drained basins. In: Willett, S.D., Hovius, N., Brandon, M.T., Fisher, D.M. (eds), Tectonics, climate, and landscape evolution. Geol. Soc. Am. Spec. Paper 398, pp. 283–294, doi.org/10.1130/2006.2398(17).

Gasse, F., van Campo, E., 2001. Late Quaternary environmental changes from a pollen and diatom record in the southern tropics (Lake Tritrivakely, Madagascar). Palaeogeogr. Palaeoclimatol. Palaeoecol. 167, 287–308, doi.org/10.1016/S0031-0182(00)00242-X.

Gourou, P., 1967. Madagascar : carte de densité et de localisation de la population (incl. 1:1,000,000 scale map). CEMUBAC and ORSTOM, Brussels and Paris, 29 p.

Granier, P., Lahore, J., 1966. Amélioration des pâturages. Le *Brachiaria brizantha.* Rev. Elev. Méd. Vét. Pays Trop. 19, 233–242, doi.org/10.19182/remvt.7410.

Granier, P., Cabanis, Y., Ellenberger, F., 1972. Etude sur les divers modes d'implantation du *Stylosanthes gracilis*. Rev. Elev. Méd. Vét. Pays Trop. 25, 569–576.

Granier, P., Cabanis, Y., 1976. Les feux courants et l'élevage en savane soudanienne. Rev. Elev. Méd. Vét. Pays Trop. 29, 267–275.

Hariniony, A.H., 2018. Etude de la sismicité des parties centrales et sud de Madagascar. Unpublished MPhil. Dissertation, University of Antananarivo, 119 p.

Helisoa, O, 1983. Les lavaka du socle malgache : distribution, évolution. Unpublished PhD thesis, université de Paris Panthéon-Sorbonne, 334 pp.

Hervieu, J., 1968. Contribution à l'étude de l'alluvionnement en milieu tropical. Mémoire ORSTOM n° 24. ORSTOM, Paris, 465 p.

Hoeblich, J., Hoeblich, J.M., 1983. L'organisation du relief dans les environs de Tananarive. Rev. Géogr. Madag. 43, 11–39.

Hossain, M.S., Dearing, J.A., Eigenbrod, F., Johnson, F.A., 2017. Operationalizing safe operating space for regional social-ecological systems. Sci. Total Environ. 584–585, 673–682, doi.org/10.1016/j.scitotenv.2017.01.095

Husson, O., Charpentier, H., Razanamparany, C., Moussa, N., Michellon, R., Naudin, K., Razafintsalama, H., Rakotoarinivo, C., Rakotondramanana, Lucien Seguy, L., 2008. Stylosanthes guianensis. Manuel pratique du semis direct à Madagascar, vol. 3, Fiches techniques plantes de couverture : légumineuses pérennes. GSDM, CIRAD, 12 p. https://www.supagro.fr/ress-pepites/PlantesdeCouverture/res/Stylosanthes.pdf

Isnard, H., 1955. Les plaines de Tananarive. Cah. Outre-Mer 29, 5–29, doi.org/10.3406/caoum.1955.1944

Knowler, D., Bradshaw, B., 2007. Farmer's adoption of conservation agriculture: a review and synthesis of recent research. Food Policy, 32, 25–48, doi.org/10.1016/j.foodpol.2006.01.003.

Kull, C., Laris, P., 2009. Fire ecology and fire politics in Mali and Madagascar. In: Cochrane, M.A. (Ed.), Tropical fire ecology. Springer, p. 171–226, doi.org/10.1007/978-3-540-77381-8_7.

Lageat, Y., Peyrot, B., 1974. Contribution l'étude de la tectonique plio-quaternaire des Hautes Terres centrales de Madagascar : la plaine de Sambaina–Ambohibary. Rev. Géogr. Madag. 25, 157–179.

Lageat, Y., Gunnell, Y. (2001). Landscape development in tropical shield environments. In: Godard, A., Lagasquie, J.-J., Lageat Y., (eds.), Basement Regions. Springer Verlag, Heidelberg, p. 173–197, doi.org/10.1007/978-3-642-56821-3_8.

Laplaine, L., 1957. Etude géologique du massif cristallin malgache à la latitude de Tananarive. Annales géologiques du Service des Mines, Paris, Fasc. 24, 84 p.

Larson, P.M., 2000. History and memory in the age of enslavement: becoming Merina in highland Madagascar, 1770–1822. Heinemann, New York, 414 p.

Lave, R., Wilson, M.W., Barron, E.S., Biermann, C., Carey, M.A., Duvall, C.S., Johnson, L., Lane, K.M., McClintock, N., Munroe, D., Pain, R., Proctor, J., Rhoads, B.L., Robertson, M.M., Rossi, J., Sayre, N.F., Simon, G., Tadaki, M., Van Dyke, C., 2014. Intervention: critical physical geography. Canad. Geogr. 58, 1–10, doi.org/10.1111/cag.12061.

Le Bourdiec, F., 1974. Hommes et paysages du riz à Madagascar. Etude de géographie humaine. Imprimerie du Foiben Taosarintanin' Madagasikara, Antananarivo, 648 p.

Lenoble, A., 1949. Les dépôts lacustres pliocènes-pléistocènes de l'Ankaratra (Madagascar). Annales Géologiques du Service des Mines, Paris, Fasc. 18, 76 p.

Lisenby, P.E., Tooth, S., Ralph, T.J., 2019. Product vs process? The role of geomorphology in wetland characterization. Sci. Total Environ. 663, 980–991, doi.org/10.1016/j.scitotenv.2019.01.399.

Longuefosse, R., 1923. L'Antsihanaka. Région du lac Alaotra. Bull. Econ. 20, 111–134.

Manconi, R., Pronzato, R., 2019. The genus Corvonspongilla Annandale, 1911 (Porifera: Demospongiae: Spongillida) from Madagascar freshwater with description of a new species: biogeographic and evolutionary aspects. Zootaxa 4612, 544–554, dx.doi.org/10.11646/zootaxa.4612.4.6.

Manconi, R., Cadeddu, B., Pronzato, R., 2015. Adaptive morpho-traits, taxonomy and biogeography of Metania Gray, 1867 (Porifera: Spongillina: Metaniidae) with the description of a new species from Madagascar. Zootaxa 3918, 39–56, dx.doi.org/10.11646/zootaxa.3918.1.2.

McCully, P., 2001. Silenced rivers: the political ecology of large dams. Zed Books, New York, 432 p.

Meyer, R., Kunreuther, H., 2017. The ostrich paradox: why we underprepare for disasters. Wharton Digital Press, Univ. of Pennsylvania, Philadelphia, 114 p.

Mietton, M., Leprun, J.C., Andrianaivoarivony, R., Dubar, M., Beiner, M., Erismann, J., Bonnier, F., Grisorio, E., Rafanomezana, J.P., Grandjean, P., 2006. Ancienneté et vitesse d'évolution des lavaka à Madagascar. Données nouvelles. Actes du Colloque du Réseau Erosion. Journées Régionales Erosion et GCES à Antananarivo, 25–27 Oct. 2005, pp. 87–94.

Mietton, M., Gunnell, Y., Nicoud, G., Ferry, L., Razafimahefa, R., Grandjean, P., 2018. 'Lake' Alaotra, Madagascar: A late Quaternary wetland regulated by the tectonic regime. Catena 165, 22–41, doi.org/10.1016/j.catena.2018.01.021.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen analysis, 2nd edn. Blackwell, Oxford.

Nédélec, A., Paquette, J.L., Bouchez, J.L., Olivier, P., Ralison, B., 1994. Stratoid granites of Madagascar: structure and position in the Panafrican Orogeny. Geodin. Acta 7, 48–56, doi.org/10.1080/09853111.1994.11105258.

Nédélec, A., Ralison, B., Bouchez, J.L., Grégoire, V., 2000. Structure and metamorphism of the granitic basement around Antananarivo: a key to the Pan-African history of central Madagascar and its Gondwana connections. Tectonics 19, 997–1020, doi.org/10.1029/2000TC900001.

Nédélec, N., Paquette, J.L., Antonio, P., Paris, G., Bouchez, J.L., 2016. A-type stratoid granites of Madagascar revisited: age, source and links with the breakup of Rodinia. Precamb. Res. 280, 231–248, doi.org/10.1016/j.precamres.2016.04.013.

Noizet, G., 1968a. Résultats géologiques nouveaux sur la plaine de Tananarive. Comptes-rendus de la semaine géologique de Madagascar 1967, pp. 13–15.

Noizet, G., 1968b. Etat des études géologiques pour l'aménagement de la plaine de Tananarive en janvier 1968. Ministère de l'Industrie et des Mines, Service géologique, 7 p.

Onofri, L., Lange, G.M., Portela, R., Nunes, P.A., 2017. Valuing ecosystem services for improved national accounting: a pilot study from Madagascar. Ecosyst. Serv. 23, 116–126, doi.org/10.1016/j.ecoser.2016.11.016.

Porras, I., Grieg-Gran, M., Neves, N., 2008. All that glitters: a review of payments for watershed services in developing countries. Natural Resource Issues No. 11, International Institute for Environment and Development, London, 129 p.

Pronzato, R., Pisera, A., Manconi, R., 2017. Fossil freshwater sponges: taxonomy, geographic distribution, and critical review. Acta Palaeontol. Polon. 62, 467–495, doi.org/10.4202/app.00354.2017.

Raison, J.P., 1969. Elevage et commerce des bœufs, Plate 37. In: Le Bourdiec, F., Battistini, R., Le Bourdiec, P., Tsiranana, P., Botokeky, L. (eds), Atlas de Madagascar. Bureau pour le développement de la production agricole, and Centre de l'institut géographique national à Madagascar, 3 p.

Raison, J.P., 1972. Utilisation du sol et organisation de l'espace en Imerina ancienne. Etudes de géographie tropicale offertes à Pierre Gourou. De Gruyter and Mouton, Paris and The Hague, p. 407–425.

Raison, J.P., 1986. L'enracinement territorial des populations Merina (Hautes Terres centrales malgaches). Fondements, modalités et adaptations. L'Espace Géogr. 15, 161–171, doi.org/10.3406/spgeo.1986.4137.

Rakoto, H., Rajaomahefasoa, R., Rasalomanana, E. H., 2017. Optimisation de la reconnaissance hydrogéologique par modélisation géophysique 2D. Cas de la zone intermédiaire Ankaraobato–Dorodosy. Madamines 1, http://madarevues.recherches.gov.mg/IMG/pdf/madamines_rakotoh._et_al._040517.pdf.

Rakotondraompiana, S., 1992. Gravimétrie de Madagascar et structure de la lithosphère. Unpublished PhD thesis, University of Antananarivo.

Rakotondraompiana, S., 2001. Dynamique actuelle de la croûte malgache à partir de données géophysiques et morphologiques. Mada-Géo 10, 42–48.

Rakotondrazafy, T., 1992. Dynamique des environnements quaternaires de Madagascar par l'étude sédimentologique, l'analyse palynologique et la diatomologie de quelques bassins lacustres. Unpublished PhD thesis, Université of Antananarivo, 172 p.

Ramboarison, R., 1990. Stérilisation des terres par les sables alluviaux. Leur recolonisation par la végétation et leur récupération par les paysans dans le cadre du bassin versant de la Sisaony. Master's Dissertation, Université d'Antananarivo, 137 p.

Randrianjafy, Z.J.N., 2006. Corrélations agroécologiques conjecturales entre savane malagasy, élevage de zébus et feu de pâturage. SMB Mada, 13 p.

Rasamoelina, H., 2017. Sécuriser de façon formelle les pâturages ? Elements de terrain de Malaimbandy. Observatoire du Foncier Madagascar, http://www.observatoire-foncier.mg/article-120/.

Rasoloarijao, T.M., Ramavololona, P., Ramamonjisoa, R., Clemencet, J., Lebreton, G., Delatte, H., 2019. Pollen morphology of melliferous plants for Apis mellifera unicolor in the tropical rainforest of Ranomafana National Park, Madagascar. Palynology 43, 292–320, doi.org/10.1080/01916122.2018.1443980.

Raunet, M., 1980. Les bas-fonds et plaines alluviales des Hautes terres de Madagascar. Reconnaissance morpho-pédologique et hydrologique, aptitude à la culture du blé de contre-saison. IRAT, 186 p.

Razafimahefa, R., Nicoud, G., Mietton, M., Paillet, A., 2012. Réinterprétation des formations superficielles pléistocènes du bassin d'Antsirabe (Hautes Terres Centrales de Madagascar). Quaternaire 23, 339–353, doi.org/10.4000/quaternaire.6431.

Rechenmann, J., 1981. La gravimétrie de Madagascar et sa relation avec la géologie. Université Paris-Sud, Orsay (France), unpublished PhD thesis.

Reimer, P., and 29 others, 2013. IntCal 13 and Marine 13 radiocarbon age calibration curves 0–50,000 Years cal BP. Radiocarbon 55, 1869–1887, doi.org/10.2458/azu_js_rc.55.16947.

Rindraharisaona, J.E., Rambolamanana, G., 2008. Evaluation des paramètres sismiques dans la partie centrale de Madagascar. Mada-Géo 12, 7–11.

Rindraharisaona, J.E., Guidarelli, M., Aoudia, A., Rambolamanana, G., 2013. Earth structure and instrumental seismicity of Madagascar: implications on the seismotectonics. Tectonophysics 594, 165–181, doi.org/10.1016/j.tecto.2013.03.033.

Roberts, G., Paul, J.D., White, N., Winterbourne, J., 2012. Temporal and spatial evolution of dynamic support from river profiles: a framework for Madagascar. Geochem. Geophys. Geosyst. 13, Q04004, doi:10.1029/2012GC004040.

Roche, M., Aldegheri, M., 1964. Monographie hydrologique de l'Ikopa et de la Betsiboka. ORSTOM. Facteurs conditionnels du régime. Vol.3 (Interprétation des résultats et caractéristiques du régime), 92 p.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, III, F.S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. & Soc. 14, doi.org/10.5751/ES-03180-140232.

Roose, E., 1982. Influences potentielles des aménagements antiérosifs des collines des hauts plateaux malgaches dans le projet de protection de la plaine d'Antananarivo contre les inondations. Rapport de mission ORSTOM, 33 p.

Samonds, K.E., Crowley B.E., Rasolofomanana, T.R.N., Andriambelomanana, M. C., Andriavanalona, H.T., Ramihangihajason, T.N., Rakotozandry, R., Nomenjanahary, Z.B., Irwin, M.T., Wells, N.A., Godfrey, L.R., 2019. A new late Pleistocene subfossil site (Tsaramody, Sambaina basin, central Madagascar) with implications for the chronology of habitat and megafaunal community change on Madagascar's Central Highlands. J. Quat. Sci. 34, 379–392, doi.org/10.1002/jqs.3096.

Sarremejean, M., 1961. La vie agricole et le calendrier du paysan malgache dans les plaines de Tananarive. Cah. Outre-Mer 56, 349–371, doi.org/10.3406/caoum.1961.2221.

Schüler, L., Hemp, A., 2016. Atlas of pollen and spores and their parent taxa of Mt. Kilimanjaro and tropical East Africa. Quatern. Int. 425, 301–386, doi.org/10.1016/j.quaint.2016.07.038.

Scroxton, N., Burns, S.J., McGee, D., Hardt, B., Godfrey, L.R., Ranivoharimanana, L., Faina, P., 2017. Hemispherically in-phase precipitation variability over the last 1700 years in a

Madagascar speleothem record. Quat. Sci. Rev. 164, 25–36, doi.org/10.1016/j.quascirev.2017.03.017.

Seguy, L., 2006. Rapport de mission à Madagascar. Projet d'appui à la diffusion des techniques agro-écologiques à Madagascar. CIRAD, Montpellier, 201 p.

Serpantié, G., 2009. L''agriculture de conservation' à la croisée des chemins en Afrique et à Madagascar. Vertigo, 9, doi.org/10.4000/vertigo.9290.

Serpantié, G., 2017. Le système de riziculture intensive ou 'SRI' à Madagascar, entre légende urbaine et innovation rurale. Anthropol. & Dévelop. 46–47, 67–99, doi.org/10.4000/anthropodev.588

Serpantié, G., Bidaud, C., Méral, P., 2013. Mobilisation des sciences dans l'écologisation des politiques rurales à Madagascar. Natures, Sciences, Sociétés 21, 230–237, doi.org/10.1051/nss/2013105

Shanmugasundaram, J., Gunnell, Y., Hessl, A.E, Lee, E., 2017. Societal response to monsoon variability in Medieval South India: lessons from the past for adapting to climate change. Anthropocene Rev. 4, 110–135, doi.org/10.1177/2053019617695343

Société Malgache d'Etudes et d'Applications Hydrauliques (SOMEAH), 2010. Etude de l'évacuation des crues dans la partie aval de la plaine d'Antananarivo. Phase 1 : Etude contextuelle des crues à Bevomanga.

Société Malgache d'Etudes et d'Applications Hydrauliques (SOMEAH–ARTELIA), 2012. Etude de l'évacuation des crues dans la partie aval de la plaine d'Antananarivo. Phase 2 : Propositions de solutions d'amélioration des crues à Bevomanga.

Stephenson, S.N., White, N.J., Li, T., Robinson, L.F., 2019. Disentangling interglacial sea level and global dynamic topography: analysis of Madagascar. Earth Planet. Sci. Lett. 519, 61–69, doi.org/10.1016/j.epsl.2019.04.029.

Straka, H., 1991. Palynologia Madagassica et Mascarenica, 2ème partie, Echantillons de surface. Trop. Subtrop. Pflanzenwelt 78, 5–43.

Straka, H., 1996. Histoire de la végétation de Madagascar oriental dans les 100 derniers millénaires. In: Lourenço, W.R. Ed., Biogéographie de Madagascar. Editions de l’ORSTOM, Paris., pp. 37–47.

Van Soesbergen, A., Mulligan, M., 2018. Uncertainty in data for hydrological ecosystem services modelling: Potential implications for estimating services and beneficiaries for the CAZ Madagascar. Ecosyst. Serv. 33, 175–186, doi.org/10.1016/j.ecoser.2018.08.005.

Villa, F., Portela, R., Onofri, L., Nunes, P.A.L.D., Lange, G.M., 2015. Assessing biophysical and economic dimensions of societal value: an example for water ecosystem services in Madagascar. In: Martín-Ortega, J., Ferrier, R.C., Gordon, I.J., Khan, S. (eds.), Water ecosystem services: a global perspective. Cambridge University Press, Cambridge, pp. 110–118, doi.org/10.1017/CBO9781316178904.014.

Walker, B.H., Carpenter, S.R., Rockstrom, J., Crépin, A., and Peterson, G.D., 2012. Drivers, ‘slow’ variables, ‘fast’ variables, shocks, and resilience. Ecol. & Soc. 17, doi:10.5751/es-05063-170330.

Wendland, K.J., Honzák, M., Portela, R., Vitale, B., Rubinoff, S., Randrianarisoa, J., 2010. Targeting and implementing payments for ecosystem services: opportunities for bundling biodiversity conservation with carbon and water services in Madagascar. Ecol. Econ. 69, 2093–2017, doi.org/10.1016/j.ecolecon.2009.01.002.

Figure legends

Fig. 1. Oblique view of central Madagascar’s relief. The intermontane basins documented in this study (white lettering), and rivers, lakes, and localities mentioned in the text, are named.

Large white box locates Figure 3, small white box locates Figure 11 (Ambohibary Basin). Digital topography based on Shuttle Radar Topography Mission (SRTM) v.3. Reference coordinate system: WGS 1984.

Fig. 2. Flow diagram summarising the research methodology.

Fig. 3. Ikopa drainage basin upstream of the Farahantsana bedrock knickzone. The Ankaratra massif, in the SW corner, is a large, late Cenozoic to Quaternary volcanic edifice resting on the Precambrian basement, and one of the highest summits in Madagascar. Blue, red, and yellow boxes show outlines of Figures 5a, 6, and 8, respectively. Digital topography based on Shuttle Radar Topography Mission (SRTM) v.3. Reference coordinate system: WGS 1984.

Fig. 4. Knickpoints and longitudinal channel profiles of five major rivers of Madagascar's Highlands (see locations in Fig. 1).

Fig. 5. Antananarivo, Madagascar's capital city in its environmental setting.
A. Antananarivo city limits and surrounding land use in 2017. Land classification based on Pléiades, Sentinel-2 and Landsat-8 imagery after Dupuy et al. (2020). In the wider Ikopa catchment north, east and south of the city, note the large footprint of the savanna biome (green on 'tanety', i.e. interfluve summits) compared to the dambo network (yellow). Even in this urbanized and highly agricultural map area in the immediate surroundings of the capital city, the savanna covers 39% of the land surface. The Different hues of green take account of proportions of tree presence, but overall tree cover is minimal in the natural grassland savannas of the Highlands despite a push for afforestation by development agencies (see Fig. 12). In the remaining 75% of the Ikopa drainage basin, grassland covers closer to 90% of the

land surface. Abbreviations: AI-Avenue de l'Indépendance; A-Andrahara; Amb-Ambohitrimanjaka; T-Tanjombato.

B. Oblique view of a suburb of Antananarivo (location in panel A), where housing between 2003 and 2017 has rapidly been crowding out rice fields and natural wetlands. CNES/Airbus and Landsat/Copernicus imagery, oblique views generated in Google Earth.

Fig. 6. Geology of the Antananarivo Basin (after Delubac et al., 1963), and location of trenches and boreholes used for documenting the basin's late Quaternary chronostratigraphy.

Fig. 7. Stratigraphy of the Antananarivo Basin sediment fill based on available civil engineering excavations and the main pollen assemblages (%) anlysed from the four dated samples in section F5. See text for data sources.

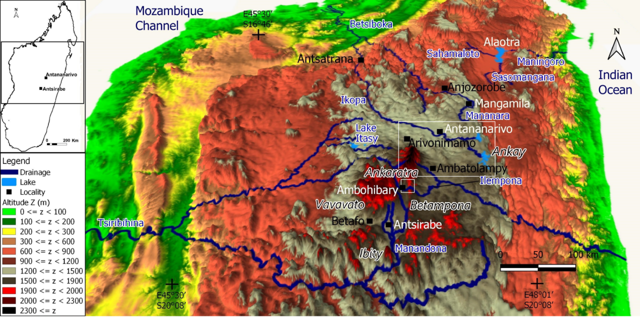
Fig. 8. Geological setting of the Bevomanga bedrock channel reach (after Noizet, 1968a, b, modified and adapted).

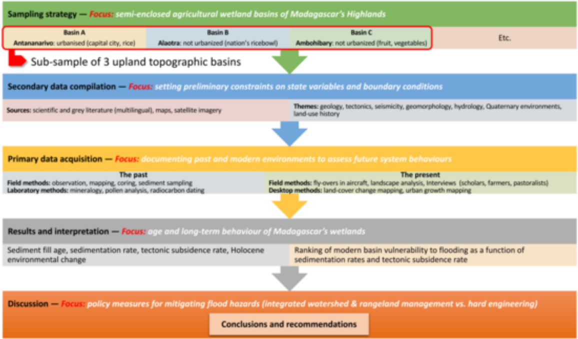
Fig. 9. Cross-section through the Antananarivo Basin sediment fill along the right bank of the Ikopa River. Profiles based on the data provided in Figures 7 and 8.

Fig. 10. Distribution of $M_L > 4$ earthquakes recorded between 1999 and 2019, and of the highest densities of lavaka in the Ikopa catchment. Mean lavaka densities mapped and computed from raw data from BDPA et al. (1994). Quadrat 1: 0.63 lavaka/km^2; Q2: 0.42 lavaka/km^2; Q3: 0.38 lavaka/km^2; Q4: 0.32 lavaka/km^2. Anywhere else in the Ikopa catchment, lavaka densities are much lower by Madagascar standards (see Table 3).

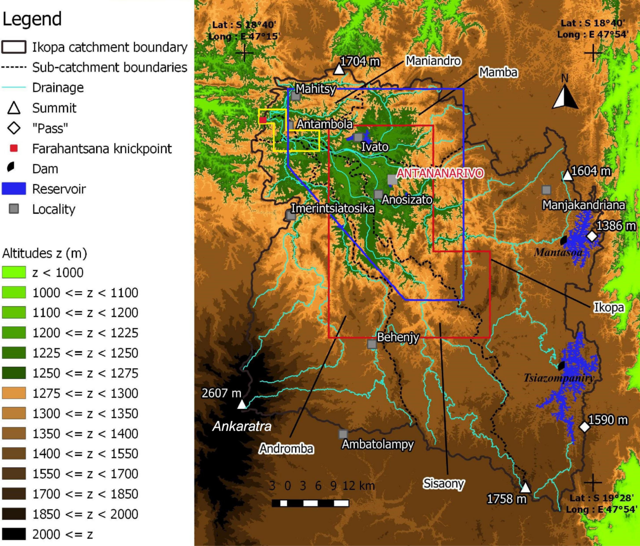
Fig. 11. The Ambohibary Basin and its outlet down the Ilempona River gorge. See location in Figure 1. CNES/Airbus imagery, oblique generated produced in Google Earth. Vertical exaggeration of relief x3, aimed at accentuating the key topographic features.

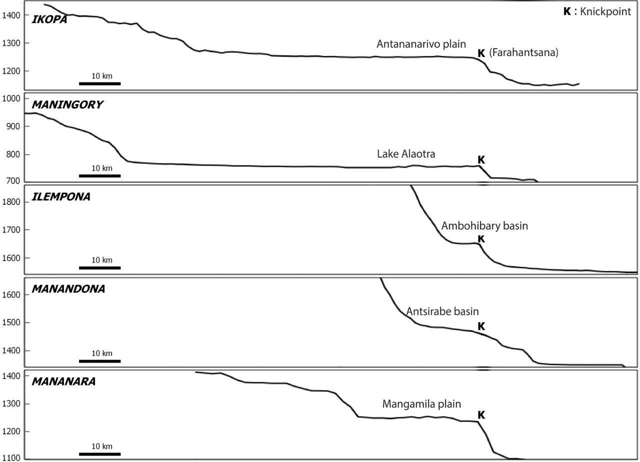
Fig. 12. The rice-growing Sasomangana valley, a rapidly subsiding tectonic sub-basin of the Alaotra graben, and the open savanna grasslands typical of Madagascar's highland landscapes. See location in Fig. 1. This landscape view summarises the diversity of disconnectivities in water and sediment discharge (sensu Fryirs, 2013) at several nested scales in the landscape, from local gullies to the floodplains typical of the semi-enclosed basins of Madagascar's Highlands and their catchment areas. 'Lohafasika' means 'source of sand'. DF: terminal debris fan generated by a locally active 'lavaka' situated outside the picture frame. In this example its feeder channel does not join the main river but is a threat to one of the major irrigation channels (here the 'Canal Principal de Rive Gauche', CPRG). P: small lake formed by ponding behind a 'lavaka'deposit. The 'lavaka' scar on the slope is already revegetated. In the foreground, note the predominantly convex hillslope profiles of the interfluves, here belonging to erosion surface 'S3', and in the background the basin's footwall uplands with range fronts scarred by large and active lavaka (L). In both cases this vast grassland savanna biome (*Aristida* sp.) is entirely devoid of agriculture and dedicated to pastoralism, either involving long-distance zebu cattle herds (S: overstocking scars along a hilltop droveway), or local village mixed herds (T: terracettes, typical of livestock trampling on hillslopes). Note how bare, overgrazed patches of soil on the hilltops can operate as contributing areas to gully-generating runoff, and how this feeds into the sediment cascade. The soils are particularly vulnerable after fires at the end of the dry season. Credits: M. Mietton.

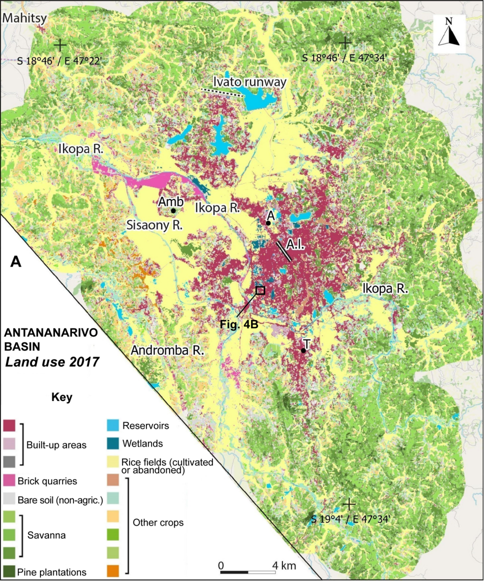

Mozambique Channel
E45°30′
S16°46′
Betsiboka
Antsatrana
Alaotra
Sahamaloto
Maningoro
Sasomangana
Indian Ocean
N
Anjozorobe
Mangamila
Ikopa
Mananara
Lake Itasy
Antananarivo
Arivonimamo
Ankay
Ambatolampy
Ankaratra
Ilempona
Ambohibary
Vavavato
Betampona
Tsiribihina
Betafo
Antsirabe
Ibity
Manandona
0 50 100 km
E45°30′
S20°08′
E48°01′
S20°08′
Antananarivo
Antsirabe
0 200 Km
Legend
Drainage
Lake
Locality
Altitude Z (m)
0 <= z < 100
100 <= z < 200
200 <= z < 300
300 <= z < 600
600 <= z < 900
900 <= z < 1200
1200 <= z < 1500
1500 <= z < 1900
1900 <= z < 2000
2000 <= z < 2300
2300 <= z

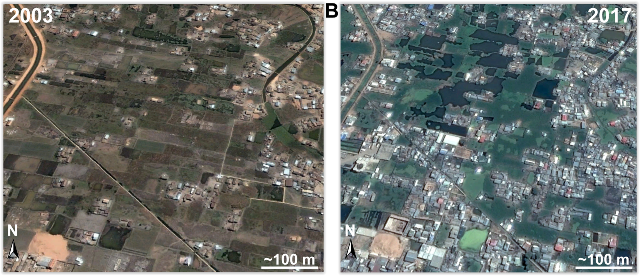


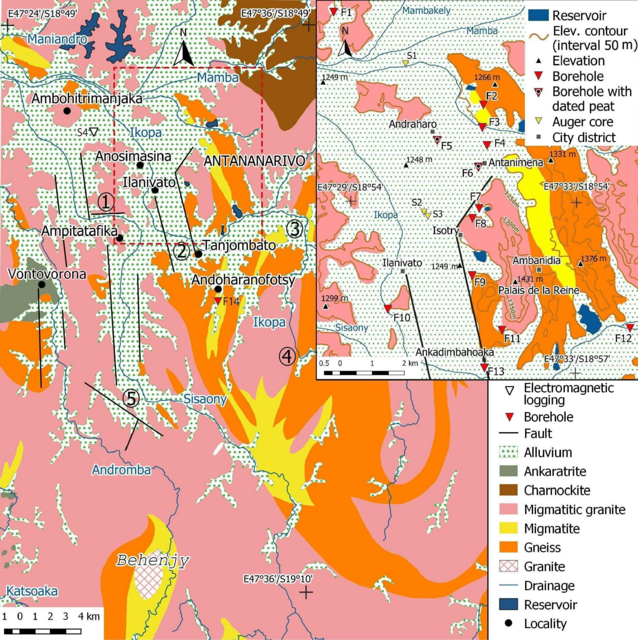
Sampling strategy — Focus: semi-enclosed agricultural wetland basins of Madagascar's Highlands
Basin A
Antananarivo: urbanised (capital city, rice)
Basin B
Alaotra: not urbanized (nation's ricebowl)
Basin C
Ambohibary: not urbanized (fruit, vegetables)
Etc.
Sub-sample of 3 upland topographic basins
Secondary data compilation — Focus: setting preliminary constraints on state variables and boundary conditions
Sources: scientific and grey literature (multilingual), maps, satellite imagery
Themes: geology, tectonics, seismicity, geomorphology, hydrology, Quaternary environments, land-use history
Primary data acquisition — Focus: documenting past and modern environments to assess future system behaviours
The past
Field methods: observation, mapping, coring, sediment sampling
Laboratory methods: mineralogy, pollen analysis, radiocarbon dating
The present
Field methods: fly-overs in aircraft, landscape analysis, interviews (scholars, farmers, pastoralists)
Desktop methods: land-cover change mapping, urban growth mapping
Results and interpretation — Focus: age and long-term behaviour of Madagascar's wetlands
Sediment fill age, sedimentation rate, tectonic subsidence rate, Holocene environmental change
Ranking of modern basin vulnerability to flooding as a function of sedimentation rates and tectonic subsidence rate
Discussion — Focus: policy measures for mitigating flood hazards (integrated watershed & rangeland management vs. hard engineering)
Conclusions and recommendations

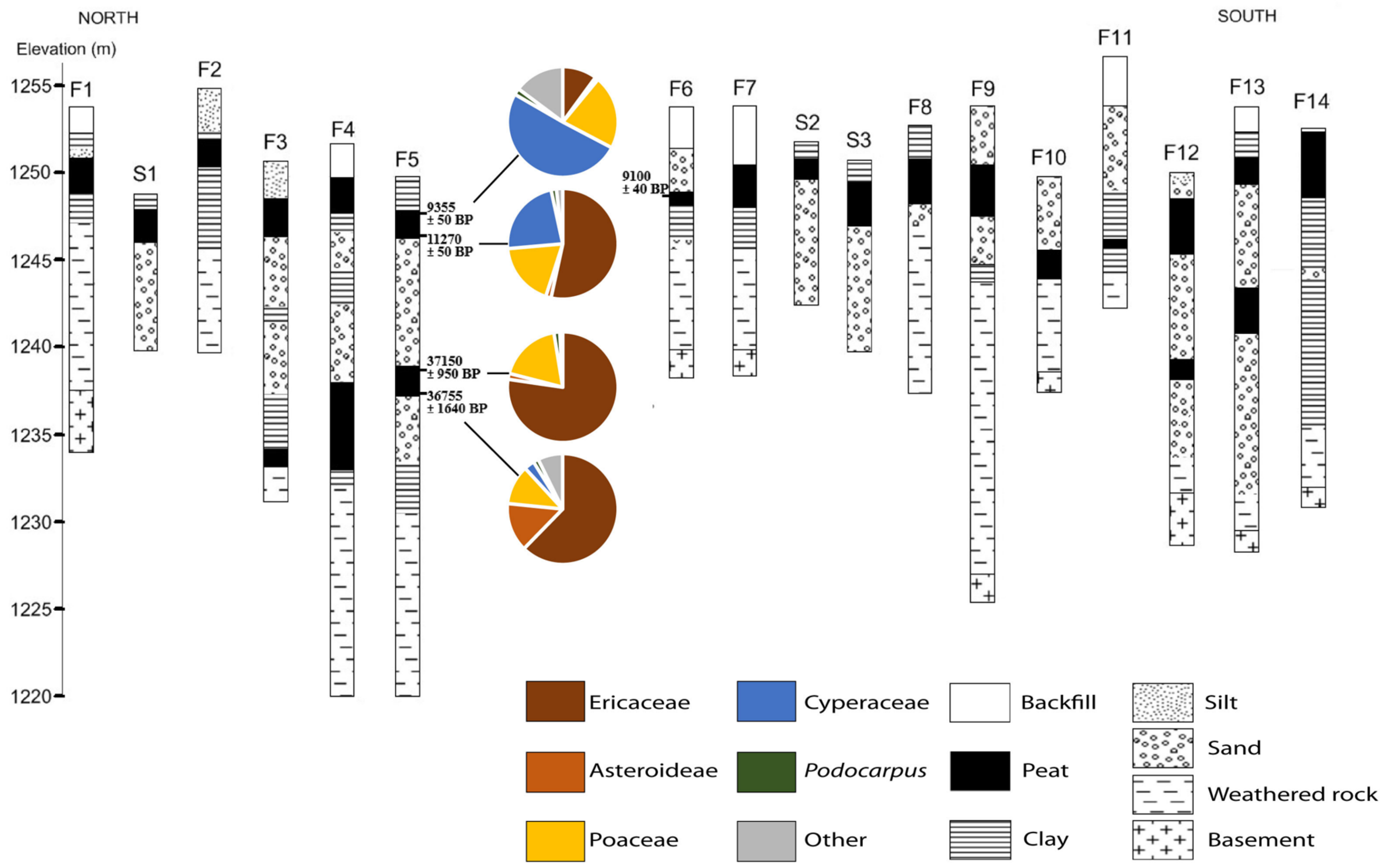

Legend
Ikopa catchment boundary
Sub-catchment boundaries
Drainage
Summit
"Pass"
Farahantsana knickpoint
Dam
Reservoir
Locality
Altitudes z (m)
z < 1000
1000 <= z < 1100
1100 <= z < 1200
1200 <= z < 1225
1225 <= z < 1250
1250 <= z < 1275
1275 <= z < 1300
1300 <= z < 1350
1350 <= z < 1400
1400 <= z < 1550
1550 <= z < 1700
1700 <= z < 1850
1850 <= z < 2000
2000 <= z
Lat : S 18°40'
Long : E 47°15'
Lat : S 18°40'
Long : E 47°54'
1704 m
Maniandro
Mamba
N
Mahitsy
Antambola
Ivato
ANTANANARIVO
1604 m
Anosizato
Manjakandriana
Imerintsiatosika
1386 m
Mantasoa
Ikopa
Behenjy
Tsiazompaniry
2607 m
1590 m
Ankaratra
Ambatolampy
Andromba
3 0 3 6 9 12 km
Sisaony
1758 m
Lat : S 19°28'
Long : E 47°54'

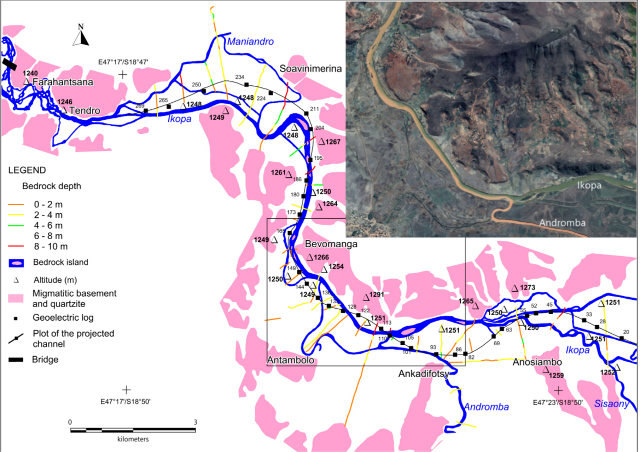

K : Knickpoint
IKOPA
1400
1300
1200
Antananarivo plain
K (Farahantsana)
10 km
MANINGORY
1000
900
800
700
Lake Alaotra
K
10 km
ILEMPONA
1800
1700
1600
Ambohibary basin
K
10 km
MANANDONA
1600
1500
1400
Antsirabe basin
K
10 km
MANANARA
1400
1300
1200
1100
Mangamila plain
K
10 km


Mahitsy
S 18°46' / E 47°22'
S 18°46' / E 47°34'
N
Ivato runway
Ikopa R.
Amb
Ikopa R.
A
Sisaony R.
A.I.
A
Ikopa R.
Fig. 4B
ANTANANARIVO BASIN
Land use 2017
Andromba R.
T
Key
Built-up areas
Brick quarries
Bare soil (non-agric.)
Savanna
Pine plantations
Reservoirs
Wetlands
Rice fields (cultivated or abandoned)
Other crops
S 19°4' / E 47°34'
0
4 km

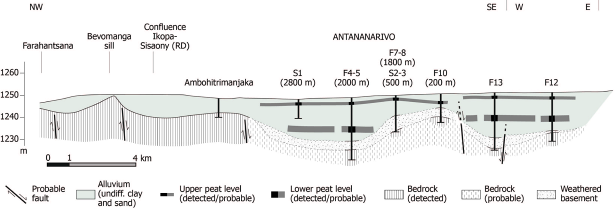

2003
N
~100 m
B
2017
N
~100 m


E47°24'/S18°49'
E47°36'/S18°49'
Maniandro
Mamba
Ambohitrimanjaka
S4
Ikopa
Anosimasina
ANTANANARIVO
Ilanivato
①
Ampitatafika
③
②
Tanjombato
Vontovorona
Andoharanofotsy
F14
Ikopa
④
⑤
Sisaony
Andromba
Behenjy
E47°36'/S19°10'
Katsoaka
1 0 1 2 3 4 km
F1
Mambakely
Mamba
S1
1249 m
1266 m
F2
F3
Andraharo
F5
F4
1248 m
Antanimena
1331 m
F6
E47°29'/S18°54'
E47°33'/S18°54'
F7
S2
S3
F8
Ikopa
Isotry
1250m
1300m
Ilanivato
1249 m
F9
Ambanidia
1376 m
1431 m
Palais de la Reine
1299 m
F10
1350m
Sisaony
F11
F12
Ankadimbahoaka
E47°33'/S18°57'
F13
0.5 0 1 2 km
Reservoir
Elev. contour (interval 50 m)
Elevation
Borehole
Borehole with dated peat
Auger core
City district
Electromagnetic logging
Borehole
Fault
Alluvium
Ankaratrite
Charnockite
Migmatitic granite
Migmatite
Gneiss
Granite
Drainage
Reservoir
Locality

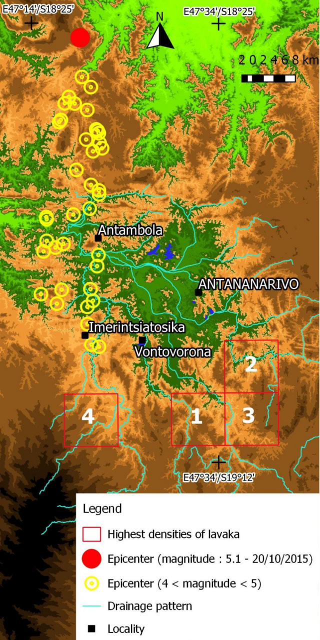

NORTH
SOUTH
Elevation (m)
1255
1250
1245
1240
1235
1230
1225
1220
F1
S1
F2
F3
F4
F5
F6
F7
S2
S3
F8
F9
F10
F11
F12
F13
F14
9355 ± 50 BP
11270 ± 50 BP
37150 ± 950 BP
36755 ± 1640 BP
9100 ± 40 BP
Ericaceae
Asteroideae
Poaceae
Cyperaceae
Podocarpus
Other
Backfill
Peat
Clay
Silt
Sand
Weathered rock
Basement



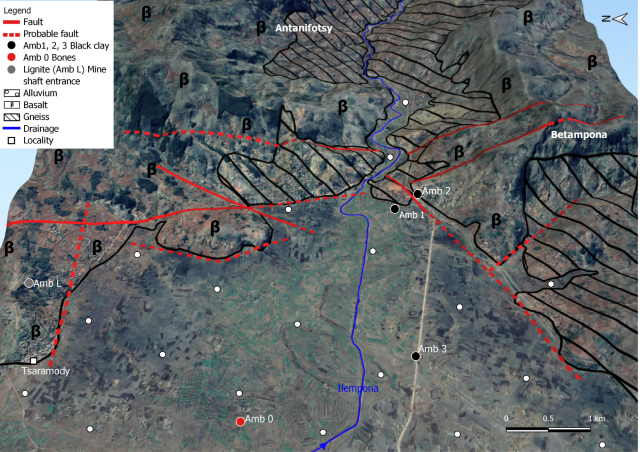
N
E47°17'/S18°47'
Maniandro
Soavinimerina
1240
Farahantsana
1246
Tendro
Ikopa
269
265
1248
250
234
1248
224
1249
211
204
1248
1267
195
1261
186
180
1250
1264
173
LEGEND
Bedrock depth
0 - 2 m
2 - 4 m
4 - 6 m
6 - 8 m
8 - 10 m
Bedrock island
Altitude (m)
Migmatitic basement and quartzite
Geoelectric log
Plot of the projected channel
Bridge
165
1249
Bevomanga
1266
1254
149
1250
144
136
1249
133
128
122
1291
1251
113
110
105
101
93
86
82
1265
1250
1273
55
52
45
1251
33
28
20
63
69
1250
1251
1251
Ikopa
Antambolo
Ankadifotsy
Anosiambo
1259
1252
Andromba
Sisaony
E47°17'/S18°50'
E47°23'/S18°50'
0
3
kilometers
Ikopa
Andromba



NW
SE
W
E
Farahantsana
Bevomanga sill
Confluence Ikopa-Sisaony (RD)
ANTANANARIVO
Ambohitrimanjaka
S1 (2800 m)
F4-5 (2000 m)
F7-8 (1800 m)
S2-3 (500 m)
F10 (200 m)
F13
F12
1260
1250
1240
1230
m
0
1
4 km
Probable fault
Alluvium (undiff. clay and sand)
Upper peat level (detected/probable)
Lower peat level (detected/probable)
Bedrock (detected)
Bedrock (probable)
Weathered basement



E47°14'/S18°25'
E47°34'/S18°25'
N
2 0 2 4 6 8 km
Antambola
ANTANANARIVO
Imerintsiatosika
Vontovorona
1
2
3
4
E47°34'/S19°12'
Legend
Highest densities of lavaka
Epicenter (magnitude : 5.1 - 20/10/2015)
Epicenter (4 < magnitude < 5)
Drainage pattern
Locality


Legend
Fault
Probable fault
Amb1, 2, 3 Black clay
Amb 0 Bones
Lignite (Amb L) Mine shaft entrance
Alluvium
Basalt
Gneiss
Drainage
Locality
Antanifotsy
Betampona
Amb 2
Amb 1
Amb L
Tsaramody
Amb 3
Ilempona
Amb 0
0
0.5
1 km


L
L
L
Sasomangana
Sasomangana
Lohafasika
CPRG
DF
S
ST
L
P
S

Table 1. Radiocarbon age constraints on sedimentation rates in Madagascar's upland basins

Sample name	Latitude (South)	Longitude (East)	Altitude (m)	Depth below surface (m)	^{14}C age (yr BP ± 1σ)	Calibrated age interval (1σ)[4] (cal BCE)	Inferred sedimentation rate (mm/yr)
Antananarivo							
Antanimena							
Ly-17145	18°53'24''	47°31'16''	1254	3	9100 ± 40	8321–8269	0.33
Andrahara							
SacA 53838	18°52'57''	47°30'32''	1250	2	9355 ± 50	8656–8561	0.21
SacA 53839	18°52'57''	47°30'32''	1250	3	11,270 ± 50	11,216–11,125	0.27
SacA 53840	18°52'57''	47°30'32''	1250	11.6	37,150 ± 950	40,396–38,834	0.31
Ly-17616	18°52'57''	47°30'32''	1250	13.5	36,755 ± 1640	40,571–36,659	0.37
Edge of Mamba valley [1]							
Gif-1479	Approx 18°48'	Approx 47°33'	1453	8-8.5	24,000 ± 100	26,200–25,921	0.34
Alaotra							
Mahakary [2]							
Ly-15506	17°41'18''	48°21'43"	775	1.4	2700 ± 35	853–812	0.52
Ly-15507	17°41'18''	48°21'43"	775	2–2.45	4140 ± 35	2864–2634	0.55
Ly-15508	17°41'18''	48°21'43"	775	6–6.50	9405 ± 40	8733–8635	0.65
Ambohitromby[2]							
Ly-10265 (GrA)	17°48'00''	48°11'30''	775	0	28,970 ± 140	31,466–31,033	n.a.
Marianina [2]							
Ly-6770 (GrA)	17°51'15''	48°23'30''	770	23	12,130 ± 50	12,156–11,978	1.9
Ly-6769 (GrA)	17°51'15''	48°23'30''	770	28.5–30	15,270 ± 60	16,678–16,513	1.9
Ly-6768 (GrA)	17°51'15''	48°23'30''	770	30–30.5	14,770 ± 60	16,110–15,929	2
Lake diatoms [3]							
	17°25'00''	48°11'30''	752	0.6–0.7	5190 ± 110	4078–3934	
	17°25'00''	48°11'30''	752	0.9–1.0	6830 ± 110	5814–5632	
Ambohibary							
Amb 1. PozA 118363	19°36'40"	47°11'13"	1655	0.3	4460 ± 40	3327–3029	0.07
Amb 2. PozA 118364	19°36'46"	47°11'16"	1663	3	26,090 ± 240	28,760–28,111	
Amb 3. PozA 118361	19°36'43"	47°10'18"	1652	3.1	22,150 ± 150	24,586–24,198	0.14
Amb L. Ly-12572	19°34'55"	47°10'38"	1710	Mine shaft	> 38,000	> 40,000	
Mangamila							
Ly-16508	18°34'42''	47°51'40''	1345	1	12,625 ± 45	13,988–12,961	0.08

Notes. 1: after Bourgeat et al., 1975; 2: after Mietton et al., 2018; 3: after Burney et al., 2004; 4: calibrated using Reimer et al. 2013 and Calib 7.10; Sample codes: Ly: Lyon CDRC; GrA: Groningen accelerator; SacA: Saclay accelerator; PozA: Poznan accelerator; Gif: Gif sur Yvette.

Table 2. Subsidence and specific denudation rates in the Alaotra and Ikopa drainage catchments

Variable of interest	Alaotra catchment (and Alaotra Basin depocentre)	Ikopa catchment (and Antananarivo Basin depocentre)
Accommodation space[1] (m^3/yr)	$3525 \cdot 10^3$	$48 \cdot 10^3$
Equivalent mass[2] (t/yr)		
Bulk density 1.2 t/m³	$4230 \cdot 10^3$	$57.6 \cdot 10^3$
Bulk density 1.8 t/m³	$6345 \cdot 10^3$	$86.4 \cdot 10^3$
Equivalent specific denudation rate (SDRc), calculated[3] (t/km^2/yr)	940 to 1380	1.3 to 2
Specific denudation rate (SDRm), measured[3] (t/km^2/yr)	2000 to 2400	360
SDRm/SDRc ratio[4]	~2	~150

Notes: 1. Accommodation space is measured as: depocentre area (km^2) x mean sedimentation rate (mm/yr), and thus is expressed here as the volume of sediment that the basin accommodates annually without overfilling, i.e., without overtopping the bedrock sill at the basin's exit point. By equivalence, it is the annual accommodation space made minimally available by the tectonic subsidence rate. The Alaotra depocentre is 2350 km^2, the Antananarivo is 160 km^2. The sedimentation rates, 1.5 and 0.3 mm/yr, respectively, are the arithmetic means of the data (treated as grouped data) presented in Table 1.

2. Equivalent sediment mass deposited is calculated here on the basis of two optional values for sediment bulk density.

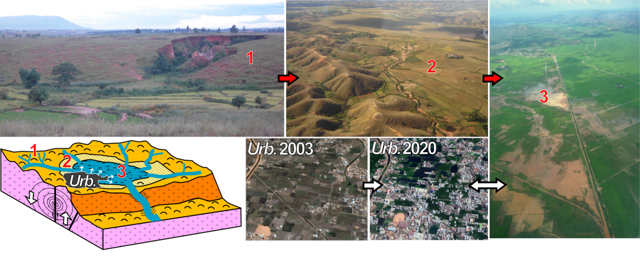
3. Specific denudation rates were measured for two montane watersheds SW and W of the Alaotra by Mietton et al. (2006), and were estimated for the Ikopa River by Roche and Aldegheri (1964). The two contributing montane catchment areas (i.e., depocentres excluded) are of similar sizes; Alaotra: 4600 km^2; Ikopa: 4300 km^2. Range of reported denudation values depends on bulk density input.

4. Note that the ratios yield a value close to 1 for the Alaotra, but a high value for Antananarivo, suggesting in the latter case a strong imbalance between sedimentation rate and subsidence rate.

Table 3. Lavaka distribution in the Ikopa catchment upstream of Farahantsana knickpoint

Sub-catchment name	Sub-catchment area (km^2)	No. of lavaka	Mean density (lavaka/km^2)
Sisaony	838.4	124	0.15
Andromba	1239	103	0.09
Ikopa	1855	93	0.05
Mamba	376	17	0.04
Maniandro	158.2	6	0.03
Total	4466.6	343	0.08

Data source: from Helisoa (1983), maps consulted in BDPA et al. (1994), and spot checks and updates using Google Earth.



1
2
3
Urb. 2003
Urb. 2020
1
2
Urb.
3