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OPINION PAPER

Community extinction: the groundwater (stygo-)fauna of Curaçao, Netherlands Antilles

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Abstract The research aimed to recollect specimens from Curaçao of the genus *Halosbaena* belonging to the rare crustacean order Thermosbaenacea, a genus with a relictual Tethyan distribution. It resulted in recording the apparent extinction of the entire, species-rich, subterranean fauna on the island that had occurred within a period of 43 years up to 2015. The composition of the groundwater fauna on Curaçao was sampled in 2015 for comparison with sampling undertake 43 years previously. Despite using the same sampling methods previously used and comprehensive coverage of the available sampling sites, no stygofauna specimen was collected from sampling in 2015 in contrast to more than 50 species collected from the initial sampling in 1973. It is hypothesised that this faunal extinction was associated with the oil industry, but it is unclear whether it resulted from petroleum pollution of groundwater drawdown or recharge. This record of the extinction of an entire ecosystem, rather than merely some members of it, is perhaps unique, but is concerning amongst the more diffuse extinction events happening globally.

Keywords Stygofauna · Groundwater · Crustaceans · Pollution · Petroleum

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Introduction

Anchialine habitats comprise inland groundwaters with marine connections that are sometimes characterised as subterranean estuaries (Bishop et al., 2015, 2020) that are especially noteworthy for their very diverse crustacean assemblages. Bundera sinkhole on Cape Range peninsula in tropical north-western Australia supports a rich anchialine fauna containing, *inter alia*, Remipedia, Thaumatocyprididae, Thermosbaenacea, and a diversity of copepods (Jaume & Humphreys, 2001; Jaume et al., 2001). This assemblage of anchialine species comprises a type of fauna recognised to have a Tethyan distribution (Jaume & Humphreys, 2001), with related faunas present also on Lanzarote (Canary Islands, Spain) and some islands on the North American Plate in the northern Caribbean region, including Quintana Roo on the Yucatán Peninsula, Mexico (Humphreys, 2017). In addition, Thermosbaenacea, seemingly unexpectedly, are widely present on Curaçao in the Netherlands Antilles (Wagner, 1994) lying on the southern rim of the Caribbean. Curaçao formed from the Cretaceous

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onwards due to subduction of oceanic crust of the Atlantic Plate beneath the Caribbean Plate (u). Physiographically, it is part of the South American Continental Plate but is generally considered as part of the Lesser Antilles Island arc (Jackson & Robinson 1994) that comprise ocean floor basalts (pillow lavas) of Cretaceous age (Hou & Li, 2018).

The thermosbaenacean genus *Halosbaena* in Australia is monotypic (Poore & Humphreys, 1992) but its broad distribution in Australia (Cape Range peninsula, Barrow Island, Robe River and Christmas Island), together with the global geographical range of the genus in Spain (Lanzarote, Canary Islands) and Japan (Ryukyu Islands), has been shown by molecular methods to comprise numerous lineages (Page et al., 2016). As an initial step to undertake molecular work on the Thermosbaenacea from these three areas I undertook a campaign to sample stygofauna from Curaçao, Netherlands Antilles, to obtain fresh samples of *Halosbaena*, as the specimens to hand (Table 1) were unsuitable, being old and preserved in formaldehyde. Wagner (1994) reported on the global occurrence of Thermosbaenacea but also included data from an intensive sampling campaign undertaken on Curaçao, mainly by J.H. Stock and J. Vermeulen between 1973 and 1984, variously by means of pumping using a biophreatical pump (Bou and Rouch, 1967), dug pits (Karaman–Chappuis method—Chappuis, 1942), or a valved net (Cvetkov, 1968). *Halosbaena acanthura* Stock, 1976 was reported to be abundant on Curaçao (Wagner, 1994).

Table 1 Thermosbaenacean specimens available in formaldehyde that prompted the sampling campaign

Tethysbaena coqui Wagner (1994)—USA
Tethysbaena stocki Wagner (1994)—British Virgin Is
Tethysbaena scitula Wagner (1994)—British Virgin Is
Tethysbaena calsi Wagner (1994)—U.S. Virgin Is
Tethysbaena haitiensis Wagner (1994)—Hispaniola
Tethysbaena juglandis Wagner (1994)—Hispaniola
Halosbaena acanthura Stock, 1976—Curaçao, Hispaniola
Tethysbaena juriaani Wagner (1994)—Hispaniola
Tethysbaena gaweini Wagner (1994)—Hispaniola

Collected from April 1978 to December 1987 variously by L. Botosaneanu, N.W. Broodbakker, J.G.M. Notenboom, D. Platvoet, J.H. Stock, H.P. Wagner, E.S.W. Weinberg, C. Williamson, F. Zijlstra, and Instituut voor Taxonomische Zoölogie (Zoölogisch Museum), Universiteit van Amsterdam. Extracted from Wagner (1994)

Methods

I sampled on Curaçao between 15 and 20 November 2015 which was 42 years after J. Stock et al. sampled the stygofauna in November–December 1973. I visited most of the accessible sites on Curaçao sampled by Wagner (1994) and sampled known and likely stygofauna sites using the same methods they employed. A Bou–Rouch pump was employed where it was possible to position the lance which I drove into the substrate to a depth of about 60 cm, if possible, using a sledgehammer. Using a manual diaphragmatic bilge pump (Whale Marine, United Kingdom) attached to the lance, I pumped about 60 l of water and filtered each 20-l bucket through a 250-µm mesh net to concentrate the residue into an attached vial. Where it was possible to excavate suitable pits, into which the interstitial water could drain, I used the Karaman–Chappuis method and recovered any fauna by straining the water through a hand net (250 µm mesh). Where open water was accessible, as in the cave, I used a Cvetkov net (250 µm mesh) drawn through the open water by hand or on a cord. The samples were concentrated and sorted under a dissecting microscope in the laboratory at CARMABI and any specimens collected were transferred to 100% ethanol in microvials.

Sample sites

I tried to replicate the sampling sites used for the original collections (Wagner, 1994)——a few having been built over——and sampled them intensively. I used a Bou–Rouch pump to sample from the shore debris barrier (coral rubble), on the shore of the Zakitó lagoon along the John F. Kennedy Boulevard, a major collection site reported in Wagner (1994), including the inner side of coral debris and 'behind the protecting barrier of beach rock', the 'land tongue of second lagoon', and the inner bay of Piscadera and Santa Marta Bay. Where the groundwater level was sufficiently shallow, I dug pits to sample using the Karaman–Chappuis method. In addition, I sampled using the Cvetkov net in Shingot Cave which contains a tidally influenced pool ~ 15 m from the coast on the west end of the island and the only cave noted to contain water (brackish) in the Curaçao Cave Inventory (2011)—most caves on Curaçao are flank margin caves now elevated above the water line although Shingot Cave is associated with a large-scale rectilinear coastal re-entrant called a boka (Kambesis et al., 2016).

Geology

The island of Curaçao began to form within the past 145 million years, beginning in the Cretaceous, as part of the Lesser Antilles island arc. Because the island was submerged for large parts of its history, reef environments formed atop thick layers of mafic volcanic rock, producing carbonate sedimentary rocks (Jackson & Robinson, 1994). Five limestone terraces formed during the past 2.5 million years of the Quaternary (Alexander, 1961*)*. As a result Curacao supports both karstic and sedimentary aquifers.

Water quality

The lava formation on Curacao has a very heterogeneous which is reflected in the varying permeability of the aquifer but it proves more of a barrier to seawater–freshwater mixing than the limestone terraces (van Leeuwen, 2022). The groundwater of the islands is brackish, due to both seawater mixing and the semi-arid climate of the islands. Infiltrating domestic and agricultural (waste)water and rainfall replenishes the aquifer and has a desalinization effect on the groundwater quality (van Sambeek et al., 2000). Wagner (1994) recorded the water quality of the sample sites which, by my calculation, had a mean chlorinity of 32.58 (range 29.52–35.64) g l^{-1}. The Caribbean Sea near Curaçao had a salinity of 36.11 (Andersen et al., 1970). Detailed assessment of the aquifer is provided by van Leeuwen (2022). In 1992, the Dutch Ministry of Transport, Public Works and Water Management advised the Curacao Ports Authority about the pollution of the Schottegat harbour. The ……. refinery site was saturated with crude oil, petroleum products, impurities in the crude oil, and substances used in the production process. The groundwater was thought to be severely polluted. Over large areas of the refinery site, which covers several 100 ha, a thick scum of oil was assumed to be present on the groundwater. The parliament of the Netherlands Antilles adopted a similar resolution, stating that Shell should be held liable for the serious damage caused to ……. groundwater, seawater, and inland waters of Curacao.

Results

During my sampling no stygofauna species was collected nor were any other aquatic species that could have been retained in a 250-µm mesh net. I observed heavy oil pollution of the water in several places both on the surface and in the groundwater.

Discussion

I am confident of this result as I have extensive experience sampling groundwater fauna using a wide range of techniques in diverse systems and in remote locations (Humphreys, 2008). From the 1973–1984 samples Wagner (1994) nominally recorded between at least 50 and 62 species of which two were terrestrial and the remainder aquatic (Table 1). He recorded *H. acanthura* from numerous locations on Curaçao, Netherlands Antilles and the nearby islands of Aves (Venezuela), Bonaire, and Jamaica. These have not been subjected to molecular research and where such has been conducted (Australia) the various populations have been found to comprise multiple clades (Page et al., 2016).

On Curaçao, *H. acanthura* was sometimes accompanied by no other stygobionts, else it occurred together with a broad range of groundwater fauna, including a variety of Amphipoda (Hadziidae, Bogidiellidae, Ingolfiellidae), Isopoda (Microcerberidae, Anthuridae), Tanaidacea, Ostracoda, Copepoda (Harpacticoida and Cyclopoida), Polychaeta, Oligochaeta, and Mollusca: Gastropoda (Wagner, 1994) (full details are provided in Table 2).

Refining of Venezuelan oil on Curaçao commenced in 1920 and represented a major part of Curaçao's economy following the abolition of the slave trade. The 100-year-old refinery (Pulster, 2015), now run as the Isla complex, was ranked in the top ten environmental pollution sites due to emissions, including groundwater pollution or depletion (Environmental Justice Atlas, 2021). The wastewater-contaminated areas are especially prominent on the coastal sites of Willemstad (Erdogan, 2021) and such

Table 2 Taxa recorded in Wagne (1994)

Cnidaria	
Foramenifera	
Mollusca	Gastropoda—*Philine* sp.
Mollusca	Gastropoda—*Caecum* sp.
Sipunculida	Undefined
Nematoda	Undefined
Archiannelida	Undefined
Polychaeta	*Microphthalmus stocki* Hartmann-Schröder, 1980
Polychaeta	*Typosyllis (Typosyllis) lutea* Hartmann-Schröder, 1960
Polychaeta	*Typosyllis (Langerhansia) botosaneanui* Hartmann-Schröder, 1973
Polychaeta	*Typosyllis (Langerhansia) broomensis* (Hartmann-Schröder, 1979)
Polychaeta	*Heteromastus filiformis* (Claparède, 1864
Polychaeta	*Namanereis pontica* (Bobretzky, 1872)
Polychaeta	*Goniatites* sp.
Polychaeta	Undefined
Oligochaeta	
Branchiopoda	Undefined
Copepoda	*Ellucana secunda* Coull, 1971; *Laophonte plana* Fiers, 1986; *Cletopsyllus rotundifera* Fiers, 1986;
Harpacticoida	Lichomolgidae. *Ellucana secunda* Coull, 1971; *Laophonte plana* Fiers, 1986; *Cletopsyllus rotundifera* Fiers, 1986
Copepoda	Undefined
Cyclopoida	Undefined
Calanoida	Undefined
Calanoida specified as 'blind'	
Copepoda	Undefined
Ostracoda	Undefined
Thermosbaenacea	*Halosbaena acanthura* Stock, 1976
Tanaidacea	Undefined
Amphipoda	*Saliweckelia emarginata* Stock, 1977
Amphipoda	*Metaniphargus curasavicus orientis* Stock, 1977
Amphipoda	Ingolfiellidae: *Ingolfiella (Gevgeliella) tabularis* Stock, 1977
Amphipoda	Ingolfiellidae: *Ingolfiella (Hanseniella) quadridentata* Stoch 1979
Amphipoda	Ingolfiellidae: *Nuuanu curvata* Vonk, 1989
Amphipoda	Undefined
Amphipoda	*Psammogammarus caesicolus* Stock, 1980
Amphipoda	Unknown specified as 'blind'
Amphipoda	Anthuridae
Amphipoda	Hadziidae
Amphipoda	Bogidiellidae
Amphipoda	Bogidiellidae—*Bogidiella* sp.
Amphipoda	Melitidae
Amphipoda	Hadziidae
Amphipoda	Unknown specified as 'oculate'
Isopoda	*Cyathura* sp.
Isopoda	Microparasellidae
Isopoda	Microcerberidae: *Microcerberus* sp.
Isopoda	Microcerberidae
Isopoda: Asellota	Janiridae: *Microjaera* sp.
Isopoda	Stenetriidae: *Stenetrium*
Isopoda	Sphaeromatiidae
Isopoda	Undefined
Cumacea	Undefined
Decapoda	*Salmoneus arubae* (Schmitt, 1936)
Decapoda	Macrura
Decapoda	Undefined
Pycnogonida	Undefined
Pycnogonida	*Hedgpethius interstitialis* Stoch, 1989
Collembola	Undefined
Diptera (larvae)	Undefined
Acari	Undefined
Pseudoscorpionida	Undefined
Hemichordata	*Amphioxus* sp.

contaminated water can have tremendous harmful effects on aquatic and terrestrial environments (Dheri et al., 2007). In Curaçao, where groundwater (from a contaminated spring) was given as a gift in a bottle to remember that this was an existing natural fresh water source in the Island's past history (Water for Life Conference, Curaçao, 2003). 'We have found that on Curaçao locals determine the quality of groundwater based on salinity and oil pollution only' (van Leeuwen, 2022).

It is likely that pollution (petroleum, pesticides, fertiliser) and habitat destruction (lowering of the water table) could have resulted in the loss of ecosystem function. Especially, as groundwater systems are specialised communities with low species richness and a truncated trophic structure as described in Gibert & Deharveng (2002). When the population size of a species falls to a low level it may no longer function as competitor, prey, or predator within the community

Fig. 1 **a** Bou–Rouch lance inserted in substrate and pump near the entrance to Piscadera Bay in front of the CARMABI Foundation Main Building [Caribbean Research and Management of Biodiversity Foundation]. **b** Sampling shingle bank on the seaward side of John F Kennedy Boulevard, Willemstad. **c** Shore near Shingot Cave (behind figure in white). **d** Bou–Rouch sampling of shore deposits along creek line. Bou–Rouch lance in foreshore deposit of Piscadera Bay with an oil drilling vessel offshore. **e** Entrance to creek, Bou–Rouch pump implanted in centre of beach. **f** Oiled water near mouth of Piscadera Bay. **g** Detail of **f**

and thus contributes to the loss of ecosystem function (Valiente-Banuet et al., 2014) and ecosystem collapse.

The oil industry is now much diminished on Curaçao, and tourism is the biggest economic sector. I hypothesise that there is a link between the oil industry and the loss of stygofauna. Whether there is a connection between the total loss of stygofauna on Curaçao and the demonstrably polluting oil refining industry would require focused research and there is, at present, a considerable contribution of wastewater, including pesticides, to the groundwater (M.J.A. Vermeij, personal communication, 2021). However, there is also demonstrable oil pollution to the groundwater remote from the refinery, the origin of which is unknown (Fig. 1, lower row) but may be linked to discharged ballast water (van Buurt, 2010) or infiltration to the groundwater of wastewater discharge (van Leeuwen, 2022). Groundwater pollution associated with the petroleum industry is widespread globally (Humphreys, 2001; Mariano & La Rovere, 2021), but this is nuanced as it is recognised that petroleum in groundwater may, in some cases, also be a source of energy for subterranean biota (Humphreys, 2000, 2002). In Australia, current recommendations are as follows:

> Groundwater should be managed in such a way that when it comes to the surface, whether from natural seepages or from bores, it will not cause the established water quality objectives for these waters to be exceeded nor compromise their designated environmental values. An important exception is for the protection of underground aquatic ecosystems and their novel fauna. Little is known of the lifecycles and environmental requirements of these quite recently discovered communities, and given their high conservation value, the groundwater on which they depend should be given the highest level of protection" (ANZECC and ARMCANZ, 2000).

Curaçao is an autonomous country within the Kingdom of the Netherlands and as such is itself responsible for environmental management (Environmental Policy Plan Curaçao, 2016–2021). In their 2013 report on the strategies for sustainable long-term economic development in Curaçao, TAC-Economics (2013) stated that environmental policy should be the first priority towards economic development. Clearly the groundwater on Curaçao has not been managed in this way and the groundwater fauna has seemingly been driven to extinction on the island.

This record of the extinction of an entire ecosystem, rather than merely some members of it, is perhaps unique, but concerning amongst the more diffuse extinction events happening globally (Tollefson, 2019).

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Declarations

Conflict of interest The author has no competing interests to declare that are relevant to the content of this article.

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