

Chapter 8

Bats and Water: Anthropogenic Alterations Threaten Global Bat Populations

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Abstract Natural bodies of open water in desert landscapes, such as springs and ephemeral pools, and the plant-life they support, are important resources for the survival of animals in hyper arid, arid and semi-arid (dryland) environments. Human-made artificial water sources, i.e. waste-water treatment ponds, catchments and reservoirs, have become equally important for wildlife in those areas. Bodies of open water are used by bats either for drinking and/or as sites over which to forage for aquatic emergent insects. Due to the scarcity of available water for replenishing water losses during roosting and flight, open bodies of water of many shapes and sizes may well be a key resource influencing the survival,

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activity, resource use and the distribution of insectivorous bats. In this chapter, we review the current knowledge of bats living in semi- and arid regions around the world and discuss the factors that influence their richness, behaviour and activity around bodies of water. We further present how increased anthropogenic changes in hydrology and water availability may influence the distribution of species of bats in desert environments and offer directions for future research on basic and applied aspects on bats and the water they use in these environments.

8.1 General Introduction

Dryland environments which include hyper-arid, arid and semi-arid regions can be highly complex and diverse, despite being occasionally perceived as simple ecosystems supporting low species diversity (Ayal et al. 2005). Aridity is described by ratio of precipitation to potential evapotranspiration ratio (P/ETP) (UNESCO 1979, Fig. 8.1) and dryland environments are ecosystems in which typically food availability is low, precipitation is limited and unpredictable, ambient temperature is high, humidity is low, and drinking water is scarce (Noy-Meir 1973). Consequently, there are large variations in primary production by plants that can strongly affect overall species diversity and interactions (Evenari et al. 1971). Furthermore, the distribution, abundance and persistence of several desert-dwelling mammal species is affected by water availability, especially during dry summer months, when the challenges of minimizing energy use and water losses is greatest (Calder 1984; Morton et al. 1995; Lovegrove 2000; Marom et al. 2006).

In desert environments, bats are an important component of the mammalian fauna. Carpenter (1969) asserted that, based on the number of species and abundance, bats are one of the most successful desert mammals, although they are outnumbered by rodents in the driest parts of the Sahara and the Namib Desert (Findley 1993). In the deserts of Israel, insectivorous bats are the most diverse

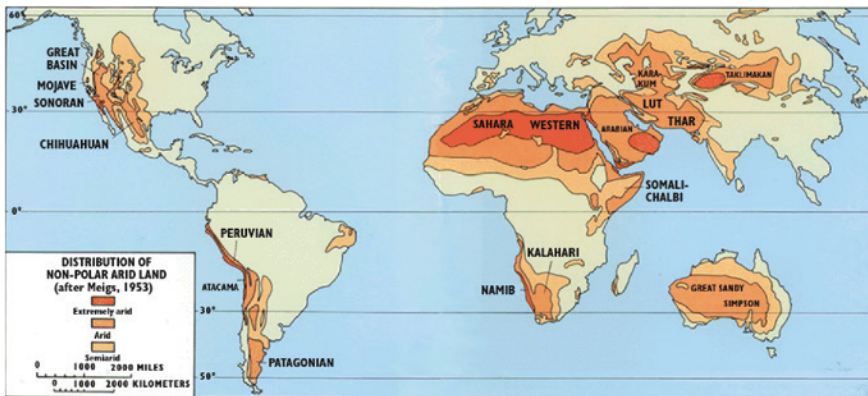


Fig. 8.1 The arid lands of the world (U.S. Geological Survey, science information services)



Fig. 8.2 A drinking event of the lesser horseshoe bat (*Rhinolophus hipposideros*) from a spring in the Dead Sea, Israel. Photo by Jens Rydell

group of mammals (Mendelssohn and Yom-Tov 1999), with 12 species recorded in the Negev Desert (Korine and Pinshow 2004) and 17 species in the Dead Sea area (Yom-Tov 1993). Benda et al. (2008) recorded 14 species of insectivorous bats in Sinai, highlighting the diversity of these mammals in desert environments. The dryland regions of South America are the most species-rich habitats of the region and have the highest number of endemic species, even when compared to the tropical lowland Amazon forest (Mares 1992; Ojeda and Tabeni 2009; Sandoval and Barquez 2013). In the Yungas dry forest of Argentina, 55 % of the bat species may be endemics (Sandoval et al. 2010). However, this area is severely under-protected and very little research has been conducted on the bat fauna (Mares 1992; Sandoval and Barquez 2013) In Mongolia, more than half of the bat species only occur in arid and semi-arid regions (Nyambayar et al. 2010).

Most bats, and in particular desert-dwelling bats, use open water sources for drinking water and/or as a foraging site (Vaughan et al. 1996; Grindal et al. 1999; Ciechanowski 2002; Campbell 2009, Fig. 8.2) with various studies reporting high levels of bat activity over open bodies of water (Rydell et al. 1994; Walsh et al. 1995; Young and Ford 2000; Mickeviciene and Mickevicius 2001; Ciechanowski 2002; Russo and Jones 2003; Korine and Pinshow 2004; Williams and Dickman 2004; Anderson et al. 2006; Davie et al. 2012; Monamy et al. 2013), making even small springs, ephemeral pools and waterholes key foraging areas for insectivorous bats worldwide (Racey 1998). Water availability was even proposed as a mechanism for elevational patterns of species richness of bats in arid mountains (McCain 2007).

In this chapter, we review our current knowledge of bats and water across regionally different semi-arid and dryland environments, and the factors that may

influence their richness, behavior and activity around bodies of water. We discuss how anthropogenic development may influence water availability and thus the distribution of species of bats in desert environments. Dryland environments are also predicted to be particularly sensitive to climate change, and we will discuss patterns by which climate disruption may further reduce water availability in arid regions. Finally, we offer directions for future research on basic and applied aspects on bats and the water they use in these environments.

8.2 Ecology of Bats and Water in Drylands Environments

8.2.1 Water Sources Used by Bats

Permanent and ephemeral pools are the central characteristic of many watersheds in dry, arid and semi-arid regions. Temporary pools have largely been ignored in management programs due to their relatively small size and apparent lack of benefit for human use (Schwartz and Jenkins 2000). However, during spring and early summer, temporary pools may serve as important foraging grounds for aquatic and terrestrial species, some of which are regionally or locally rare and/or endemic (Nicolet et al. 2004). Temporary pools in the Negev Desert had equivalent levels of species richness of bats and activity to permanent pools (Razgour et al. 2010) and the activity of bats was reduced significantly when bodies of open water were dried (Korine and Pinshow 2004), highlighting the importance of pools of all shapes and sizes to desert wildlife. In the arid regions of Mongolia, even sub-optimal water sources such as small human-dug wells and salty lakes are used by bats and are an important resource for their continued survival (Nyambayar et al. 2010). Conservation efforts should therefore focus on those sources offering only temporary water availability because although they support similar bat species richness and activity levels as permanent pools, they are less likely to be protected due to their ephemeral nature.

That said, the importance of permanent pools can be underestimated if landscape availability of water is not considered through time. Geluso and Geluso (2012) analyzed 34 years of data in relation to capture rates gathered at a single drinking site, which was sampled once yearly, in the San Mateo Mountains of New Mexico. They found that in non-drought years capture success was significantly lower because bats were more dispersed across the landscape. However, in drought years, capture rates at the only available water source skyrocketed, thereby indicating the importance of open-water to local species of bats.

Data gathered on foraging patterns of bats in Utah indicated a strong affinity by *Myotis* bats for riparian and edge habitats as compared to other surrounding areas (Rogers et al. 2006). Similarly, Grindal et al. (1999) showed that bat activity levels were significantly greater in riparian versus upland areas in British Columbia and capture rates were higher for females than for males indicating that female bats may be more dependent on water-driven attributes of a particular area. Williams

et al. (2006) sampled across 22.5 km of the Muddy River floodplain in the Mojave Desert in Nevada, which was highly disturbed by long-standing flood control, livestock grazing, and the invasion of non-native plant species, and found that the riparian woodland habitat, which represents less than 1 % of the area, accounted for greater than 50 % of all bat activity. Areas of historically less disturbed mesquite bosque habitat maintained higher bat activity than more disturbed areas. Fortunately, restoration of habitats can increase local species richness. In Arizona, red bats (*Lasiurus blossevillii*), which had not been reported before, were captured along riparian-restoration areas of the lower Colorado River. The Arizona myotis (*Myotis occultus*), presumed extirpated, was also captured after restoration (Calvert 2012).

In Africa, there is evidence that bat activity is higher around bodies of water than in adjacent areas. For example, in two regions in southern Africa, bat abundance was higher in riverine habitat than in adjacent, dryer savannah (Rautenbach et al. 1996; Monadjem and Reside 2008). Differences in species richness and diversity between riverine and savannah habitats were not the same in the two regions. In the Kruger National Park, there was no difference in bat species richness or evenness between riverine habitat and savannah (Rautenbach et al. 1996). In contrast, at another site in Swaziland, the riverine habitat had higher species richness and diversity (Monadjem and Reside 2008). In both regions, the two assemblages differed in the relative densities of the various species, with the savannah assemblages forming a subset of the riverine assemblages (Rautenbach et al. 1996; Monadjem and Reside 2008). This reinforces the notion that bat assemblages in less mesic regions are extensions of bat assemblages in more mesic regions, but that not all species are inclined to make use of less mesic habitats when conditions are favorable. Some of them, particularly fruit eating bats (e.g. *Epomophorus crypturus*; Thomas and Fenton 1978) may be restricted to riverine habitats (Monadjem and Reside 2008).

Australian studies also indicate high levels of bat activity around bodies of water (Lumsden and Bennett 1995; Williams and Dickman 2004; Griffiths et al. 2014a). Young and Ford (2000) found that species richness of bats, abundance, and capture success in the semi-arid Idalia National Park was greatest in areas adjacent to water, with 97 % of captures occurring at sites with water. Bats in Uluru National Park and the north-eastern edge of the Simpson Desert predominantly use oasis habitats that have permanent or temporary water sources even in years with higher than average annual rainfall (Coles 1993; Williams and Dickman 2004). Multiple species of Australian insectivorous bats have even been recorded flying, foraging, and perhaps drinking over hypersaline environments (Laegdsgaard et al. 2004; Gonsalves et al. 2012; Griffiths et al. 2014a, b). *Pteropus* species in New Guinea have been recorded drinking seawater (Iudica and Bonaccorso 2003) but the prevalence of bats drinking hypersaline water in arid environments is not understood, despite natural hypersaline water bodies being common in arid and semi-arid areas in Western Australia (Halse et al. 2003; Timms 2005). In the arid regions of Mongolia, bats are mostly frequently found in association with water (Dolch et al. 2007; Davie et al. 2012).

8.2.2 *Bodies of Water as a Drinking Source*

Water sources that are used by bats are likely to be pools in streams, lakes, ponds, slow-flowing streams and rivers and artificial bodies of water with similar properties such as farm and urban dams (Jackrel and Matlack 2010; Sirami et al. 2013), canals (e.g. Lisón and Calvo 2011), cattle troughs, swimming pools and settling ponds at waste water treatment facilities (Vaughan et al. 1996; Abbott et al. 2009; Naidoo et al. 2013, 2014) and mines having natural seepage (Donato et al. 2007; Griffiths et al. 2014a).

Both the size and accessibility of the water source influence whether a bat can drink from it. Bats drink water by swooping over a water source while lapping at the surface (Harvey et al. 1999). Because bats drink on the wing, small and more maneuverable bats are able to drink from smaller pools, whereas less maneuverable bats need a large surface area of water to skim (Tuttle et al. 2006). In the Negev Desert, Razgour et al. (2010) found that both within and between pools, species richness of bats and activity significantly increased with pond size. Furthermore, manipulations that decreased pond size led to a significant reduction in species richness and activity and affected the bat assemblage composition. The size and situation of artificial water sources similarly affect their use by bats. In the arid Texas Panhandle, USA, bats preferentially drank water from larger livestock tanks that were full and had only light vegetation around. They tended to avoid smaller, half-full tanks with denser vegetation around them (Jackrel and Matlack 2010). Although there are many anecdotal observations (Nickerson and O'Keefe 2013) of bats drinking from swimming pools there have been no formal studies of this.

Despite the central nature of drinking and water availability for bats, there are a surprisingly small number of studies addressing this topic in Europe, even though many species do drink at open water sources regularly to rehydrate (e.g. Russo et al. 2012). Some appear more sensitive than others to water deprivation because of their stricter dependence on water habitats. For instance, in water-denial experiments Daubenton's bat, *Myotis daubentonii*, a species selectively dwelling in riparian habitat and above bodies of open water, has been found to undergo a greater body mass loss and to show signs of dehydration earlier than the brown long-eared bat, *Plecotus auritus*, a forest bat (Webb et al. 1995). Drinking sites are also of chief importance for European bats outside the semiarid Mediterranean region. In the Bavarian Forest, Germany, oligotrophic, acidic ponds are used by over a dozen species of bats for drinking (Seibold et al. 2013). Likewise, in the Italian Apennines, water cattle troughs built for traditional livestock breeding are frequently used to drink by over a dozen species of bats. Such small (often less than 15×1.5 m) pools of water are locally of extreme importance (Russo et al. 2010, 2012) for several threatened species (Fig. 8.3). These pools also concentrate insects, so bats occasionally forage there, but their importance for drinking is overwhelming (Russo et al. 2012). The disappearance of traditional livestock breeding due to rural depopulation in many Apennine areas has led to the abandonment of the cattle troughs, implying an unstudied yet potentially high cost for bat



Fig. 8.3 Cattle troughs used by drinking bats in the Italian Apennines. Photo by Luca Cistrone

populations (Fig. 8.3). In Italian forests, bats also drink from the small ephemeral pools which form following heavy rain and only last few days or weeks (D. Russo, pers. obs.). Eavesdropping on other drinking bats is likely to play an important role in locating such sites and this behaviour is typical of species with manoeuvrable flight such as the barbastelle bat, *Barbastella barbastellus*, and the greater horseshoe bat *Rhinolophus ferrumequinum*.

8.2.3 Bodies of Water as a Foraging Habitat

The tendency for higher insect abundance near water sources attracts bats to use water sources as foraging habitats. Furthermore, calm surface water provides a less cluttered acoustic signal return from the echolocation pulses (Mackey and Barclay 1989; Siemers et al. 2001), and there is some evidence, at least for echolocating bats, that activity over calm pools of water is higher than that over fast-flowing riffles (von Frenckell and Barclay 1987). Bat activity in a transect from dry woodland savannah to riverine habitat in southern Africa was correlated with insect abundance—both bat activity and insect abundance were higher in riverine habitat (Rautenbach et al. 1996) suggesting that bats were attracted to this habitat because of the feeding opportunities it provided.

Drought is known to reduce the abundance of insects in temperate zones (Frampton et al. 2000) and thus affect reproduction in insectivorous bats (Rhodes 2007). An eight year study by Bogan and Lytle (2011) on aquatic insects living in two study pools of a formerly perennial desert stream in the Whetstone Mountains of Arizona, USA, showed that complete water loss followed by intermittent flow caused a catastrophic regime shift in community structure that did not recover to the pre-drying configuration even after four years. Ledger et al. (2011) found significant reduction in and suppression of secondary productivity by drought that could have severe constraining effects on terrestrial vertebrate predator populations, and Love et al. (2008) found similar effects in Arkansas, USA. Furthermore,

desert bats in Arizona responded to artificial-light-induced food patches (Fenton and Morris 1975) and one would presume this would be similar when small pools of water create swarms of high insect density. All of these data together suggest that small water sources with intermittent flow are vitally important as foraging sites to at least some insectivorous desert bat species.

In Europe, three species of bats are aquatic habitat specialists: Daubenton's bat, *M. daubentonii*, the long-fingered bat, *Myotis capaccinii*, and the pond bat, *Myotis dasycneme*. Besides taking insects in flight by aerial hawking, they typically forage very close to the water surface, from which prey is gaffed with their large feet or the inter-femoral membrane and transferred to the mouth while on the wing (Kalko and Schnitzler 1989; Siemers et al. 2001). Chironomidae and Trichoptera are frequent prey items of these bats (e.g. Biscardi et al. 2007; Krüger et al. 2012). *M. capaccinii* may seize adult chironomids from the water surface as they emerge from pupal casings. Trawling bats mainly forage over calm water whose surface is free from ripples (Rydell et al. 1999) as echoes from clutter interfere with prey detection (Siemers and Schnitzler 2004). On windy nights, *M. capaccinii* and *M. daubentonii* are less active (Russo and Jones 2003), presumably because wind reduces prey density and generates ripples on the water surface affecting target detection. In such circumstances, bats forage at sheltered sites where water is calmer (Lewis and Stephenson 1966; Lewis 1969).

Several other species of bats frequent riparian habitats to forage and/or drink, especially the soprano pipistrelle, *Pipistrellus pygmaeus* (e.g. Nicholls and Racey 2006), Nathusius' pipistrelle, *Pipistrellus nathusii* (Flaquer et al. 2009), and other *Pipistrellus* spp. (Scott et al. 2010), Schreiber's bat *Miniopterus schreibersii* (Serra-Cobo et al. 2000) and noctules, *Nyctalus* spp. (Rachwald 1992; Racey 1998; Vaughan et al. 1997). The stricter reliance on riparian habitats is one of the main ecological factors distinguishing *P. pygmaeus* from its sibling *P. pipistrellus* (but see Warren et al. 2000) and allowing interspecific niche partitioning and thus coexistence (Oakeley and Jones 1998; Nicholls and Racey 2006; Davidson-Watts et al. 2006; Sattler et al. 2007). However, local factors such as elevation or landscape composition may influence differences across species. At larger scales, the presence of main rivers and wetland areas are important as migratory paths and offer important stopover sites to migrating bats across Europe (Flaquer et al. 2009). Rivers and riparian vegetation also constitute important linear landscape elements used for navigation by several European bats (Serra-Cobo et al. 2000; Russo et al. 2002).

As might be expected given the above, the quality of foraging areas lacking water is influenced by their distance to water. In Portugal, proximity to a drinking water source increased foraging habitat quality for Mehely's horseshoe bat *Rhinolophus mehelyi* and *M. schreibersii* (Rainho and Palmeirim 2011). Similarly, a radio-tracking study of *R. mehelyi* in Spain showed that although this species hunted predominately in forest, the foraging areas were always within 500 m of a water source (Salsamendi et al. 2012), possibly to allow for easy rehydration between foraging bouts or perhaps to take advantage of water-emergent forest insects. In historic landscape parks of England (Glendell and Vaughan 2002) as

well as in German forests (Kusch and Idelberger 2005) the relative area of available water surface is an effective proxy for levels of bat activity.

Australian bats have also been documented preferentially foraging around water sources. When compared to other habitat types in the Simpson Desert, more feedings buzzes were recorded around permanent and temporary water sources (Williams and Dickman 2004). Bats will also forage over hypersaline water bodies but more feeding buzzes are recorded over freshwater sites (Griffiths et al. 2014b). There is also evidence (e.g. Aldridge and Rautenbach 1987; Schoeman and Jacobs 2003, 2011; Naidoo et al. 2011, 2013) that insects associated with freshwater habitats (e.g. Plecoptera, Ephemeroptera and Trichoptera) occur in the diet of southern African bats.

8.2.4 Water, Roosts and Reproduction

The propensity for female bats to choose roost sites that are relatively high in ambient temperature is thought to help them save metabolic energy by allowing for continued gestation of the young during torpor (Speakman et al. 1991; Adams and Thibault 2006; Daniel et al. 2010). The cost of such a choice in roost sites in arid regions, however, is the propensity for high-levels of evaporative water loss during the diurnal roosting cycle (Webb 1995) and this is further exacerbated when females are lactating (Kurta et al. 1990). The only quantitative field study to assess the need for drinking water by lactating female bats in drylands used PIT-tagged lactating and non-reproductive females from a maternity colony of fringed myotis (*Myotis thysanodes*) in Colorado, USA. Adams and Hayes (2008) found that lactating females visited to drink an average of seven times more per night than did non-breeding adult females. In addition, lactating females visited to drink consistently night after night regardless of daily relative humidity and temperatures, whereas non-reproductive females visited more when temperatures were high and relative humidity low (Adams and Hayes 2008).

In addition, Adams (2010) synthesized 13 years of capture data from the same field sites in Colorado, USA and found that summer mean precipitation had the highest correlation with reproductive frequency followed closely by mean stream discharge rates. Of these two, the latter showed the most abrupt effect on bat reproduction. When stream discharge rates were lower than 7 m/s, the frequency of reproductively active females captured plummeted, in some years by as much as 50 %. When female reproductive condition was plotted against mean stream discharge, the frequency of lactating females tracked the amount of available water, whereas the frequency of pregnant females was not correlated. This suggests that during drought years pregnant females may give birth, but do not have access to enough drinking water to support lactation. O'Shea et al. (2010) using mark/recapture of big brown bats, *Eptesicus fuscus*, at maternity colonies in Ft. Collins, Colorado, USA found that first year survival was lowest in bats born during a drought year, although other factors were also at play.

Several species of bats have been found to roost close to bodies of water to minimize the energy expenditure required to reach important drinking or foraging sites (Racey 1998; Korine et al. 2013). The need to drink directly after emerging from the roosts may be the main factor determining the proximity of roosts to water, especially for maternity colonies (Racey 1998). *M. daubentonii*, whose foraging strictly depends on water habitat, often uses bridges over rivers, as well as buildings or cavity-bearing trees in the immediate surroundings of riparian biotopes (Racey 1998; Parsons and Jones 2003; Lučan and Radil 2010; Encarnaçao 2012). Several other species, such as Natterer's bat (*Myotis nattereri*), pipistrelles (*Pipistrellus* spp.) and brown long-eared bat, also tend to roost in landscapes comprising bodies of water that provide drinking and foraging opportunities (Racey 1998; Entwistle et al. 1997; Oakeley and Jones 1998). Floodplain forests of central Europe host important reproductive colonies of tree-roosting noctule bat *Nyctalus noctula* (Görföl et al. 2009). *Myotis macropus*, an Australian species, has a variable roosting behaviour but the primary force behind roost selection is proximity to waterways (Campbell 2009).

8.3 Threats to Water Sources Used by Bats

In drylands, where water resources are scarce, any loss of or degradation to open water source, such as a reduction in water quality, may create cascading affects that will be harmful to the wildlife that depends on it. When bats drink from a polluted source they ingest toxins directly and during foraging they indirectly ingest toxins that may have bio-accumulated within their insect prey. For example, if insect larvae feed on microorganisms in polluted water, they concentrate the pollutants in their bodies and when they metamorphose into adults these are consumed by bats. The effect of environmental chemical containments on bats was reviewed in 2001; most studies have occurred in Europe (~50 %) and North America (~34 %) mostly pertaining to organochlorine insecticides (58 %), metals (30 %), and polychlorinated biphenyls or PCBs (13 %) (Clark and Shore 2001). There are hardly any reports on the effect of polluted water on bat activity and richness in the drylands of North Africa, the Middle East and South America. Levels of bat activity in the Negev Desert were very high over wastewater treatment ponds (Korine and Pinshow 2004), however species richness was low and the majority of the activity was attributed to Kuhl's pipistrelle (*Pipistrellus kuhlii*). Pilosof et al. (2013) showed that sewage pollution in the Negev desert affected the immune response of Kuhl's pipistrelle and Naidoo et al. (2014) reported on DNA damage to bats that forage at wastewater treatments work.

8.3.1 *Loss of Sources of Water*

An estimated two-thirds of Earth's freshwater flowing to oceans is obstructed by anthropogenic development (Nilsson and Berggren 2000), with approximately 75,000 dams in the USA alone and the majority of natural wetlands having been destroyed as well. Although not the scope of this chapter, it is important to mention that for bats, wetlands provide critical foraging habitat (Johnson et al. 2008; Rainey et al. 2006) with absolute area and connectivity of wetlands being important components for foraging (Lookingbill et al. 2010).

Indeed, a recent report on total wetland loss in the USA from 2004–2009, showed a 25 % reduction from the previous reporting period. In addition, a total of 95,000 acres of saltwater wetlands and 265,720 acres of freshwater wetlands were lost (Dahl and Stedman 2013). The situation is exacerbated in the western USA, where livestock grazing has damaged at least 80 % of stream and riparian ecosystems (Belsky and Matzke 1999). The consequences for bats are illustrated by observed declines in bat activity as related to flow-reduction and drying along the San Pedro River in Arizona. Moreover, these declines corresponded to declines in insect availability at perennial sites and both bat activity and insect activity declined to imperceptible levels in areas where the river dried up (Hagen and Sabo 2012).

European rivers, lakes and wetlands are among the most seriously altered ecosystems. Human impact has caused a major structural or chemical degradation of such ecosystems with fatal repercussions for their associated biota (e.g. Abel 1996). Alteration of European rivers has often led to the loss of channel features, floodplain connectivity and structure of bank vegetation. A threatened vespertilionid, *M. capaccinii*, selects foraging sites where water is less polluted and riparian vegetation better preserved. Along with the loss or disturbance of suitable cave roosts (Papadatou et al. 2008), riparian habitat alteration poses the main threat to this bat (Biscardi et al. 2007).

Australian rivers have the highest variation in flow and flooding in the world (Williams 1981; Puckridge et al. 1988). Anthropogenic activities such as extraction and diversion of water have had adverse impacts on rivers in the arid-zone of Australia (Walker 1985; Kingsford and Thomas 1995). High natural variation in water availability coupled with anthropogenic activities and climate change has the potential to catastrophically affect arid-species that depend on water availability (Roshier et al. 2001; McKenzie et al. 2007; Saunders et al. 2013).

A major concern associated with natural rivers and lakes in urban areas is that they may be polluted by runoff from roads or other sources. When bats drink from these sources, they ingest these pollutants directly or indirectly by feeding on aquatic-emergent insects. Sources of pollution of farm and golf course dams include feces from livestock and wild animal, nitrate and phosphate in fertilizers, metals, pathogens, sediments and pesticides. Unfortunately, little research has been done on the use of polluted urban water sources by bats and the probable health impacts on bats. The little evidence that does exist suggests that at least

some species of bats may not avoid polluted bodies of water in arid areas (Pilosofo et al. 2013; Korine et al. 2015). In Durban, South Africa bat abundance and species richness were higher over a polluted than over an unpolluted river and bat feeding activity (measured by feeding buzzes in the echolocation sequences) was also higher at the polluted river. There was, however, no difference in insect diversity between the two rivers (Naidoo et al. 2011) and, with the exception of a single species, Rufous mouse-eared bat, *Myotis bocagii*, proportions of prey items in the diets of bats did not correspond to their proportion in the insect fauna. *M. bocagii* fed predominantly on Diptera and this was also the most abundant insect in the insect light traps (Naidoo et al. 2011).

8.3.2 Mining

Mining is a major anthropogenic source of environmental destruction and contamination globally. Toxins associated with extensive mining operations, in particular, gold mining is well documented. Cyanide used to extract gold from ore is commonly stored in open ponds, some of which are 200 acres in size. The actual numbers of bats, and other wildlife killed by drinking at these ponds is poorly understood and very difficult to track as many affected individuals either become submerged, or die from drinking contaminated water after leaving the site. Between 1980 and 1989, 34 % of all known mammals killed at cyanide ponds used for mining gold in California, Nevada, and Arizona were bats (Clark and Hothem 1991).

Other heavy metals used in mining operations such as arsenic, cadmium, chromium, copper, lead, mercury, methyl mercury, nickel, and zinc have been found in bat carcasses. In Arizona, USA where at least 20 % of bat populations are in decline (King et al. 2001), Mexican free-tailed bats (*Tadarida brasiliensis*) living 8 km from a major copper smelting mine had accumulated significant levels of atmospheric mercury in their tissues (Petit 2007). In another study in Arizona, pallid bats (*Antrozous pallidus*), western pipistrelles (*Parastrellus hesperus*), and *T. brasiliensis* had elevated mercury levels in their liver and muscles that they most likely acquired via drinking from contaminated free-water sources (Reidinger 1972; see also Syaripuddin et al. 2014).

Besides contaminated ponds, natural water flows through thousands of abandoned mines in the western USA (used by bats for hibernaculum and maternity roosts) may be highly contaminated with heavy metals. For example, at Sheep Tank Mine overlooking the Colorado River in Arizona, barium, manganese and zinc were detected in soil samples at concentrations 10 times normal levels and *E. fuscus* captured at the site had higher concentrations of these elements than those collected from three other sites (King et al. 2001). Other species included in the study had high arsenic levels as well as other contaminants (copper, lead, barium, manganese, and zinc) (King et al. 2001). Bats and other terrestrial vertebrates can also be exposed to high levels of contaminants by ingesting aquatic emergent

insects living in toxic streams and High levels of bioaccumulated cadmium and zinc are known to occur as far as 381 km downstream from the pollution source, whereas lead was found to be transferred from sediments to chironomids (midges) only as far as 40 km downstream (Cain et al. 1992). Thus, large stretches of streams and rivers far from the point source of contamination pose threats to bats and other aquatic and terrestrial wildlife.

Bats are also known to fly and possibly forage/drink over gold mines in Australia (Donato and Smith 2007; Smith et al. 2008). High bat activity was recorded over gold mine water bodies containing cyanide (Griffiths et al. 2014a). Griffiths et al. (2014b) suggested that elevated salt levels in water bodies at gold mines may decrease bat activity, foraging, and drinking. Bats, including the Vulnerable (IUCN 2014) ghost bat, *Macroderma gigas*, have also been recorded around an Australian copper mine in the Great Sandy Desert, although the mine's effects on individuals or the population is unknown (Read 1998).

Africa is rich in mineral resources and this makes mining activities relatively common so likely a serious threat to water quality and therefore to bats. A matter of grave concern is that no research has been done in Africa in this regard. This situation prevails despite evidence that mining activities do pollute surface water in Africa (Olade 1987; Naicker et al. 2003).

8.3.3 Agriculture

Organochlorine pollution of streams and rivers, and other sources, is of major concern for bats (see Bayat et al. 2014 for review). Experimental testing of organochlorine insecticides such as DDT on two species widely distributed throughout the USA, found that *Myotis lucifugus* was approximately twice more sensitive than were *E. fuscus*. Furthermore, juvenile *E. fuscus* were 1.5 times more sensitive than adults (Clark et al. 1978). In addition, tests showed that individuals of *T. brasiliensis* poisoned with DDT survived for some time but later died of DDT poisoning mobilized from fat during active flight after being starved (Clark et al. 1975). Laboratory studies also show that presence of organochlorine in tissues can accelerate the catabolism of fat, causing DDE-dosed bats (*M. lucifugus*) to lose weight faster than control bats (Clark and Stafford 1981). Although banned in the USA in 1972, significant levels of DDT and DDE have been documented in tissues collected from bats foraging and drinking at the Rocky Mountain Arsenal Superfund Site (O'Shea et al. 2001). High DDT concentrations are also found in *M. lucifugus* tissues in the Eastern United States (Kannan et al. 2010). Furthermore, post-ban persistence of DDT in USA bats has been verified by sampling guano at roost sites (Clark et al. 1982; Reidinger and Cockrum 1978; Bennett and Thies 2007). DDT has also been found in bat tissues in Australia despite being banned since 1987 (Mispagel et al. 2004; Allinson et al. 2006). DDT for agricultural use was essential banned worldwide in 2001, but recent work from Africa showed that DDT is probably still being used and accumulating in the tissues of multiple species of bats (Stechert et al. 2014).

The two most common agricultural pollutants are nitrogen and phosphorus and sources of these pollutants include inorganic and organic fertilizers, leguminous crops, septic tanks, farm and municipal waste water treatment facilities, and, in the case of phosphorous, run-off from groundwater discharge and atmospheric deposition. An excess of these nutrients is the leading cause of aquatic eutrophication (Shabalala et al. 2013). Inorganic pollutants such as metals from agricultural and industrial run-off can also accumulate in these sites as well as in the tissues of insects using these bodies of water. Bats feedings on such insects are thus at risk of ingesting high levels of toxic metals such cadmium, chromium and nickel (see Naidoo et al. 2013).

8.3.4 Waste Water

European bats foraging in aquatic habitats are known to be largely exposed to toxic heavy metals which bioaccumulate in their insect food (Pikula et al. 2010). Organic pollution of rivers is also known to affect bat foraging, but its effects are variable. A British study compared the differences in bat activity found respectively upstream and downstream from sewage outputs and showed that downstream activity of pipistrelle bats decreased whereas that of *M. daubentonii* increased relative to upstream sites (Vaughan et al. 1996). The latter species is thought to benefit from the higher downstream abundance of pollution-tolerant prey such as chironomids. However, an Irish study obtained opposite results, with *P. pygmaeus* being more common downstream of sewage effluent discharges than *M. daubentonii* (Abbott et al. 2009). Park and Cristinacce (2006) compared the effects of two types of sewage treatment works for foraging bats: those with percolating filter beds, often hosting many insects potentially important for bats, and the “activated sludge” system—gradually replacing the former—in which sewage and bacteria-laden sludge are mixed and agitated so that they prove inhospitable for the invertebrate fauna. The study showed that both insect biomass and bat activity were higher at percolating filter beds and that bat activity there was comparable to that recorded at nearby natural foraging habitats. However, bats may run serious risks when foraging at such sewage treatment works: endocrine disrupting chemicals, which may alter the endocrine functions in exposed animals, have been found to concentrate in bat insect prey at percolating filter beds, with potentially harmful effects on foraging bats (Park et al. 2009).

There has been very little research in Africa on the concentration of pollutants in tissues of bats and no work on the long and short term effects of these pollutants on the health of bats. There is some evidence of the presence of the toxic metals cadmium, chromium and nickel in tissues of African bats foraging at sites downstream of waste water treatment plants (Naidoo et al. 2013). Furthermore, bats foraging over waste water treatment facilities display increased haematocrit and DNA damage and decreased antioxidant capacity in muscle tissue compared to bats that forage over unpolluted sites. Although these effects were not lethal they may result

in long-term negative effects on the health of bats (Naidoo et al. 2014). These metals were probably ingested by bats via their insect prey.

There is evidence that aerial insects developing in sewage sludge and waste water at sewage treatment plants can accumulate pollutants that could disrupt endocrine functioning (Park et al. 2009). However, a similar study on the activity of the insectivorous bat, the banana bat, *Neoromicia nana*, at three urban rivers systems above and downstream of where sewage effluent enters these rivers revealed that the relative abundance and feeding activity of *N. nana* were higher at polluted sites downstream of where sewage entered the system than at the unpolluted sites upstream (Naidoo et al. 2013). In this case the bats may have been attracted by the higher abundance of dipterans over the polluted sites. Diptera were the dominant prey items in both the insect fauna at the polluted sites and in the diets of the bats (Naidoo et al. 2013). This also appeared to be the case for *M. bocagii* which also fed predominantly and opportunistically on Diptera (Naidoo et al. 2011).

The response by bats to rivers affected by waste water treatment effluent may vary both between and within species. In North America (Kalcounis-Rueppell et al. 2007) and England (Vaughan et al. 1996), some species were more active upstream from where waste water effluent entered the rivers while others were more active downstream. It appears that these differences arise from the differential effects of eutrophication on insect prey as well as on the responses of bats. Some species take advantage of eutrophication that causes an increase in the abundance of their preferred prey, and other species which apparently do not feed on insects that are affected by eutrophication, prefer to forage in less polluted habitats. Furthermore, these differences may also result from differences in the foraging behavior of the same species at different sites. For example, *N. nana* fed opportunistically on the small abundant dipterans at wastewater polluted sites, but at unpolluted river sites fed selectively on insects from other orders (Naidoo et al. 2013).

Another major anthropogenic compound found in open bodies of water in the USA is polychlorinated biphenyl or PCB, a common industrial waste product that was banned by the United States in 1979 and the United Nations in 2001. PCB poisoning in pregnant *M. lucifugus* led to stillborn young (Clark and Krynsky 1978). Aquatic-emergent insects are key exporters of contaminants to terrestrial ecosystems (Menzie 1980; Runck 2007) and data show significant lateral transfers of PCBs to terrestrial riparian predators such as spiders, reptiles and amphibians (Walters et al. 2008). High concentrations of PCB's have been found in fat tissues of *M. lucifugus* in New York and Kentucky (Kannan et al. 2010). Along the fresh water tidal river, the Biesbosch, in the Netherlands, direct transfer from river sediments to chironomids to pond bats occurred in concentrations known to cause negative reproductive effects in mink (Reinhold et al. 1999). Frick et al. (2007) investigated the effects of an accidental chemical spill (metam sodium) on Yuma myotis (*Myotis yumanensis*) in California and found reduced female juvenile survival, but not adult female survival. The spill-affected population declined significantly during the first years of the study. Although the population increased in year four, this also coincided with an end to an extensive regional drought. Controlled

experimental exposure to Lindane (an organochlorine used in wood preservatives) at sublethal levels in *P. pipstrellus* increased 24 h metabolic rates of a 7.3 g individual by 15 % and in a 6.3 g individual by 23 %, thereby posing a significant threat to survivorship of free-living individuals (Swanepoel et al. 1999) and showing that sub-lethal exposure can affect energetic balance.

8.4 Mitigation and Restoration

Both the availability and distribution of water in drylands have been drastically altered by natural processes such as decline in annual precipitation, and by anthropogenic developments such as irrigation for agriculture, over exploitation of groundwater and human-induced climate changes.

8.4.1 Restoration of Water Sources and Related Habitats

Most wetlands have been altered globally due to anthropogenic disruption, pollution, and outright destruction. In some, but too few, places, humans have begun to restore some of those wetlands. For example, in the USA, the Sierra Nevada Conservancy is working in cooperation with State Parks, the Department of Toxic Substances, California State University Chico and others, to identify mercury sources and potential remediation strategies for an abandoned hydraulic mine discharging sediment and heavy metals into the Yuba River and removing mercury from dredged sediment that have accumulated in the Combie Reservoir.

In California, restoration of the Cosumnes River floodplain re-established bat activity that broadly corresponded with flooding and an increase in aquatic emergent insects (Rainey et al. 2006). Furthermore restoration of riparian habitat, frequently damaged by cattle as well as other anthropogenic uses, and wetlands commonly destroyed by human development, is essential and is occurring in some areas, but well below necessary levels for bat conservation (Goodwin et al. 1997).

Despite some of the negative effects highlighted in the previous section concerning waste water effluent, wastewater reclamation is an important process especially in areas where water is scarce (Anderson et al. 2001). Wastewater can be used to construct artificial wetlands that provide habitat for wildlife if the water is properly treated (Greenway and Simpson 1996; Fujioka et al. 1999; Greenway and Woolley 1999; Greenway 2005). Some studies have found that increased nutrient loads, such as those caused by wastewater effluent may have a positive effect on insect and bat abundance both in US and European streams (Kokurewicz 1995; Vaughan et al. 1996; Abbott et al. 2009). One US study found that bat activity and foraging levels were the same up-stream and down-stream of wastewater discharge but community structure was altered, with the riparian-specialist *Perimyotis subflavus* being more abundant (Kalcounis-Rueppell et al. 2007).

8.4.2 Artificial Water Sources

One way to overcome the diminishing of natural water sources in many drylands is the development of artificial catchments which are widely used for wildlife management (Krausman et al. 2006). There has long been controversy regarding the effects of catchments on local wildlife, in which critics argue that these developments do not yield expected benefits to game species and may have opposing impacts such as predation (O'Brien et al. 2006).

Small artificial ponds may be of utmost importance for wildlife (Russo et al. 2012). The large-scale expansion of intensive agriculture in semiarid Mediterranean climates has often been sustained by hydraulic engineering works, to cope with the scarcity of natural irrigation water. In southeastern Spain, Lisón and Calvo (2011) studied the effects on bats of a water transfer channel and a related network of irrigation ponds in a mixed landscape of traditional and intensive agricultural landscape. In general, artificial bodies of water had a positive effect on bat activity, but this mainly regarded common, generalist species (*P. pipistrellus* and *P. pygmaeus*) most likely because of the absence of foraging habitats suitable for more specialized species (those bearing a higher conservation value) such as riparian vegetation. In Catalonia, rice paddies sustain high bat activity, providing large amounts of insect prey. However, roost availability was the main limiting factor and installing bat boxes represents a valuable strategy to increase bat populations (Flaquer et al. 2006). In the arid Ikh Nart Nature Reserve in Mongolia, significantly more bats were caught at natural springs relative to human-made wells and no bats were captured at sites without water (Davie et al. 2012). This suggests that at least for this area, replacing lost natural water sources with artificial ones may not be as effective for preserving bat populations as conserving natural water sources.

Paradoxically, the creation of large water reservoirs may prove harmful to the entire bat community. Rebelo and Rainho (2009) looked at the effects on bats of the largest reservoir in Europe, created by construction in 2001 of the Alqueva dam, in Alentejo, Southern Portugal. The project led to the deforestation and submersion of an area of ca. 250 km². Consequently, bat populations were affected by the sudden disappearance of ca. 200 km of riparian habitat, together with large-scale roost loss and the replacement of important habitat with a vast homogeneous one which was not used by foraging bats. Noticeably, bat activity showed a strong decline in the submerged areas but increased in the surrounding unaffected habitat.

The expansion of Mediterranean species into surrounding arid wildlife communities may have a negative impact on local populations such as competition for the use of pools for drinking and foraging. Nine of the 12 Negev species of bats (Korine and Pinshow 2004) are associated with arid areas, and the Kuhl's pipistrelle, the European free-tailed bat (*Tadrida teniotis*), and the rare lesser horseshoe bat (*Rhinolophus hipposideros*)—are Mediterranean species that have expanded their distribution into the Negev in the twentieth century (Yom-Tov and Mendelsohn 1988). The most common bat in some desert habitats and in

particular at artificial water sites in the Negev is Kuhl's pipistrelle (Korine and Pinshow 2004). The expanded distribution is probably linked to human settlements and in particular to artificial bodies of water since non-desert species of bats must drink on a daily basis and drink more frequently compared with desert-dwelling bats (Razgour 2010). Kuhl's pipistrelle competes for the use of pools for drinking and foraging, resulting in temporal and spatial partitioning between local desert bat species (Razgour et al. 2011). The documented competition between Kuhl's pipistrelle and desert-dwelling bat species (Polak et al. 2011; Razgour et al. 2011), combined with the increasing development of bodies of open water in the Negev and other drylands, may lead to further resource competition resulting in loss to the region's biodiversity. Korine et al. (2015) have shown that species richness and activity of desert dwelling bats did not differ between artificial and natural bodies of water in the Negev desert, however several species of bats drank or foraged only at natural bodies of water.

8.5 Conclusion and Future Directions

Human population growth, land use change and habitat loss have led to massive habitat alterations and destruction, particularly of water sources in arid regions. The availability of water (temporary/permanent) appears to have a strong positive influence on species of bats richness and activity. This suggests that large temporary pools are important for the conservation of bats in arid environments. A reduction in the availability of temporary pools, due to intensification of arid conditions, is expected to predominantly affect species of bats that forage over water, and will most likely increase interspecific competition for foraging space above the pools. These problems are likely to be exacerbated in species of bats that are able to extend into arid areas because of their association with humans. Studies on the distribution of bats in drylands on a large scale should be the focus of future research to understand how climate change and introduction of artificial bodies of water affect species distribution, activity and richness. Studies are strongly needed in arid regions to understand the best and most efficient way to provide safe artificial water sources for bats that can mitigate increased incidences of drought due to climate change and, in some cases, the total loss of available water, especially in the more temperate arid regions with shorter growing seasons. For example, placement of artificial water sources near maternity roosts is instrumental in arid temperate areas with shorter growing seasons (Adams 2010). However, the introduction of artificial bodies of water may promote invasion by non-native species and range expansion of others, leading to resource competition. In regions of Europe likely to become water-stressed because of human induced climate changes, bats may be affected as they may lack the physiological means to cope with water limitation (Sherwin et al. 2013).

Africa, as well as other arid areas such as the Negev and the Mongolian deserts, has a high diversity of bats but compared to other areas of the world its bat fauna

has been little studied. Fundamental research is most needed throughout Africa and other arid zones on how often bats need to drink and whether this varies across species, geographically and seasonally. Comparative studies on bats with distributions restricted to arid regions and species that have populations in mesic and arid regions would be particularly informative in this regard. For example, the diversity of renal capacities and habitat use amongst African species of bats of the same family (Happold and Happold 1988), and the emergence of robust family level phylogenies (e.g. Stoffberg et al. 2010) provide an excellent opportunity to study the evolution of renal form and function in African bats in an ecological context. Special focus should be placed on research determining the extent to which African bats are reliant on artificial water sources. Such research should target arid zone species of bats, especially those species that live in close association with humans because these are the species likely to be impacted by insufficient or polluted water sources.

Research is also needed on whether all water sources are used for both drinking and foraging and how bats respond to decreases in water quality as a result of pollutants. Do certain species of bats avoid drinking from low quality bodies of water as shown by Korine et al. (2015)? Would bats still use polluted bodies of water for feeding but not for drinking? If so, how do they detect low quality water, do they do so before they are adversely affected by it and do they have alternative water sources? How are desert-dwelling bats affected by pollutants in water or by water-borne toxins and pollutants in the insect fauna, and are such bats able to deal with such pollutants physiologically?

Although least is known about bats and water in sub-Sahara Africa, studies thus far in other regions of the world are in their infancy in terms of understanding the long-term effects of decreased water availability on bat and other wild populations. Due to human destruction of wetlands and riparian habitats as well as unsustainable human population growth that more and more is utilizing greater amounts of fresh water, availability of fresh water to sustain wildlife populations are reaching critically low levels, especially in areas suffering from extended droughts due to human-induced climate disruption. Because water is a key ingredient of all life, focus on this topic needs to increase and because bats act as ‘canaries in a global coal mine,’ studies concerning bats and water are key to better management of water resources in natural and artificial areas.

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