

What have we learned about water developments for wildlife? Not enough!

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Species inhabiting arid environments often contend with ambient temperatures as high as 45°C and that are coupled with unpredictable availability of resources. Free-standing water has been considered to be a resource that limits distribution and abundance of many species of wildlife in arid regions of the United States, and water developments have been used since the 1940s to improve habitat. Provision of water has been assumed to be beneficial to wildlife, particularly during dry seasons and in those environments where surface water is scarce. In recent decades, degradation of naturally occurring water sources resulting from anthropogenic factors has further decreased surface water available to wildlife. Nevertheless, water developments have become controversial, in part, because their ecological effects are difficult to quantify. We compiled and evaluated recently available literature for evidence of effects of water sources on wildlife populations. Critics have expressed concern about water quality, species-specific benefits, mortalities of entrapped animals, enhancement of predator populations, increases in predation rates near water sources, and competition; in general, these negative effects are not supported by available data and remain highly speculative. Positive effects of water developments on wildlife have been documented, and species thought previously not to use free-standing water do so when it is available. Long-term studies with strong experimental designs are needed to examine the effects of water developments on productivity, recruitment, and survival of wildlife populations.

Key Words: competition, disease transmission, forage, habitat improvements, predators, ungulates, water availability, water developments, water quality

All life requires water for survival, and access to surface water may affect population dynamics of many species, especially those inhabiting arid environments. Availability of free-standing water has been considered a factor that limits the distribution and abundance of many wildlife species in the deserts of the southwestern United States (Rosenstock et al. 1999, Morgart et al. 2005). Although wildlife managers generally have assumed that provision of water has been beneficial to native species inhabiting environments where surface water is scarce, multiple authors have questioned that assumption (Broyles 1995; Brown 1998; Krausman and Czech 1998; Rosenstock et al. 1999, 2004; Bleich et al. 2005; Rabe and Rosenstock 2005; Valeix et al. 2008).

Since the 1940s, wildlife professionals have used water developments in desert ecosystems to enhance wildlife habitat (Rosenstock et al. 1999, 2004; Bleich et al. 2005; O'Brien et al. 2006). Since then, extensive loss or degradation of naturally occurring sources of water including springs, rivers, and their tributaries has occurred across the arid West, a result largely of urban, agricultural, transportation, and industrial development (Krausman and Etchberger 1995, Rosenstock et al. 1999, DeStefano et al. 2000, Krausman et al. 2006). In addition, rivers and their tributaries have been altered by water diversion, groundwater pumping, flood control structures, dams, and community development, with large scale impacts to riparian vegetation (Lynn et al. 2008). Those anthropogenic alterations have lowered water tables and decreased availability of free-standing water that is used by wildlife (Lynn et al. 2008, Patten et al. 2008). As a result, water developments have been used to offset the loss of surface water and have been effective in doing so (Longshore et al. 2009, Bleich et al. 2010, Whiting et al. 2011).

Water developments are designed to be perennial sources of water for wildlife, and can be man-made, or are natural water sources that have been modified by humans (Dolan 2006). The three main goals of water developments have been to (1) mitigate the loss of natural water sources resulting from human interference; (2) expand species distributions; and, (3) improve performance of wildlife populations (Marshall et al. 2006b). Nevertheless, provision of water for wildlife has become a controversial practice (Rosenstock et al. 2004; Bleich 2005; Bleich et al. 2005, 2006; Mattson and Chambers 2009), in part because the ecological effects of water developments are difficult to quantify and few studies have been implemented to determine population-level effects (Brown 1998, Rosenstock et al. 2004).

A number of investigators have summarized literature regarding the construction, use, and deployment of wildlife water developments, or their effects on wildlife (deVos and Clarkson 1990, Krausman and Etchberger 1996, Ballard et al. 1996, Krausman and Czech 1998, Rosenstock et al. 1999), but information on the subject has increased substantially during recent years. For example, Whiting et al. (2011) described a several-fold increase in citations concerning water developments and bighorn sheep (*Ovis canadensis*), between 1980 and 2011. Our general objective was to call attention to pertinent information that recently has become available and, specifically, to evaluate that literature for evidence of effects of water developments on wildlife populations. In doing so, we make reference to literature on the requirements of desert species for free-standing water, and the effects of free-standing water on water content and quality of forages. We also reviewed literature that addressed the most common concerns about water developments, including water quality, entrapment, use by predators, predation, competition, recruitment and productivity of wildlife populations, and behavior of prey species.

FREE-STANDING WATER REQUIREMENTS AND FORAGING

Desert species must contend with ambient temperatures often approaching 45°C, and unpredictable availability of resources, including water (Elder 1956, Hervert and Krausman 1986, Hazam and Krausman 1988, Feldhamer et al. 1999). Those species have adapted to survive and reproduce with limited availability of water through a variety of behavioral and physiological mechanisms (Cain et al. 2006, 2008a). Primary routes of water loss include cutaneous evaporation, pulmonary evaporation, defecation, and urination (Turner 1973, Cain et al. 2006). For females with dependent young, lactation is an important route of water loss as well (Cain et al. 2006). Indeed, female mule deer (*Odocoileus hemionus*) visiting water developments have been observed to consume more water than males, presumably due to increased water requirements associated with lactation (Rosenstock et al. 1999, Cain et al. 2006). Nevertheless, few studies examining physiological effects of water loss in wildlife have been conducted in the arid regions of western North America. As a result, little is known about the water balance of most ungulates inhabiting that region (Cain et al. 2006), and researchers must consider the potential for pre-formed or metabolic water to affect water demand when considering wildlife responses to water developments (Larsen et al. 2010).

Some desert ungulates, such as the Sonoran pronghorn (*Antilocapra americana sonoriensis* — one of the most endangered large mammals in North America [Morgart et al. 2005]), previously were thought to obtain sufficient moisture from forage. Indeed, Broyles (1995) claimed that Sonoran pronghorn do not require or use free-standing water, a notion refuted by Morgart et al. (2005), who used remote photography, interviews, and documents in agency files to confirm use of surface water by that specialized ungulate. Thus, previous claims that Sonoran pronghorn do not drink water when it is available are unfounded, and appear to have been based on subjective opinions or anecdotal evidence (Czech and Krausman 1999, Morgart et al. 2005). Throughout their range, pronghorn have been more abundant in areas with free-standing water than in more xeric areas, and individuals with larger home ranges indicate forage and water are sparsely distributed (Rosenstock et al. 1999, Morgart et al. 2005, Hervert et al. 2005). Further, Sonoran pronghorn were observed closer to water more frequently than were random locations, and areas farthest from water were used less than expected (deVos and Miller 2005). Moreover, Sonoran pronghorn were attracted to areas disturbed by the military because of the availability of new forbs and free-standing water that collected in bomb craters (Hervert et al. 1997, Krausman et al. 2005).

Among herbivores, dependence on free-standing water and rates of forage consumption are associated with the moisture content of forage (Jarman 1973, Morgart et al. 2005, Dolan 2006). Thus, availability of free-standing water may be a limiting factor for populations of large herbivores (at least seasonally) if water requirements are not met by forage consumed (Hervert et al. 2005, Morgart et al. 2005). For example, Sonoran pronghorn increased consumption of the fruits of chain fruit cholla (*Opuntia fulgida*), which have water content up to 85%, during the driest times of the year (deVos and Miller 2005, Hervert et al. 2005). Nonetheless, chain fruit cholla is low in protein (4%) and individuals foraging primarily on chain fruit cholla likely trade off nutritional content to satisfy water requirements (Hughes and Smith 1990, Hervert et al. 2005). Indeed, Sonoran pronghorn that died during a severe drought had high amounts of chain fruit cholla in their rumens, indicating that water requirements were high but that nutritional requirements were not met

(Hervert et al. 2005). Hervert et al. (2005) concluded that presence of chain fruit cholla may be the single most important variable explaining habitat-use patterns of Sonoran pronghorn, and noted that those specialized ruminants might use other areas with more nutritional forage if they could otherwise meet their water requirements.

Water developments can allow resident species, including species of concern, to extend their distribution into otherwise suitable habitat that remained unused because of the lack of free-standing water (James et al. 1999; Lynn et al. 2006; Bleich 2008, 2009). In Arizona, mule deer began using seasonal ranges throughout the year after construction of water developments and were able to use habitat that was previously unsuitable for part of the year due to an absence of free-standing water (Rosenstock et al. 1999). Yet, some investigators did not detect a response in movement patterns after water was provided within mule deer habitat, possibly because of time lags between provision of water and use of that source by mule deer (Krausman and Etchberger 1995). Based on the results of aerial telemetry, water developments initially appeared to have a minor effect on habitat use and distribution of mule deer; however, remote photography subsequently confirmed substantial use by those ungulates (Marshal et al. 2006a, 2006c). That discrepancy was best explained by activity patterns of mule deer, frequency of telemetry data, and timing of telemetry flights (Marshal et al. 2006c). Other investigators have claimed that quality of forage may be more significant to wildlife than access to free-standing water in determining home-ranges and movement rates, especially during periods of drought (Morgart et al. 2005, Cain et al. 2008b). Bleich (2009), however, emphasized the importance of forage-mediated density dependence and its relationship to the effectiveness of water developments for wildlife. Moreover, Cain et al. (2008b) suggested that managers consider habitat suitability based on the vegetative community when evaluating locations for placement of water developments.

Water developments could result in population declines of mule deer, mountain sheep, or pronghorn (hereafter, native ungulates) if forage, rather than water, was the limiting resource (Krausman and Czech 1998, Parker and Witkowski 1999). Indeed, addition of wildlife water developments in arid areas has been suggested to concentrate foraging by native ungulates around the water developments that could decrease abundance of forage at a local scale (Krausman and Czech 1998, Marshal et al. 2006b). If native ungulates stay relatively close to water during times of water scarcity rather than ranging more widely, the resulting increase in foraging intensity could reduce availability of forage nearby; such effects should be evident in the vegetation surrounding water developments, or by differences in forage biomass between areas near, when compared to those removed from, water developments (Marshal et al. 2006b). Marshal et al. (2006b), however, reported no effect of water developments on forage biomass, and no change in gradient of forage biomass between desert washes with water developments and those without. Native ungulates used the washes near water developments in their study area, but had no effect on nearby vegetation (Marshal et al. 2006b). As a result, Marshal et al. (2006b) concluded that any difference in forage biomass could not be attributed to the presence of water developments, despite strong evidence that native ungulates used those sources of water. In addition, available evidence suggests that piosphere effects (disturbance gradient centered around the water site [Lange 1969]) do not occur as a result of wildlife use of water developments and, thus, have little effect on small vertebrates (i.e., desert adapted reptiles or rodents) residing nearby (Cutler and Morrison 1998).

While most water developments are intended to benefit game species, they are intensively used by nongame wildlife, including a variety of birds and bats (Rabe and

Rosenstock 2005, Krausman et al. 2006, Lynn et al. 2006, O'Brien et al. 2006). Unlike many mammals, most desert birds have not evolved unique physiological mechanisms for water conservation (Bartholomew and Cade 1956, O'Brien et al. 2006) and, with the loss or degradation of natural water sources, water developments in desert environments may be critically important to resident birds (Krausman et al. 2006, Lynn et al. 2006, O'Brien et al. 2006). Although use of water developments by avian migrants is reported to be low, water developments are used year-round by resident species including house finches (*Carpodacus mexicanus*), northern mockingbirds (*Mimus polyglottos*), Gila woodpeckers (*Melanerpes uropygialis*), mourning doves (*Zenaidura macroura*), and Gambel's quail (*Callipepla gambelii*) (Krausman et al. 2006, O'Brien et al. 2006, Lynn et al. 2008). Visitation by resident species increases during the hottest hours of the day, suggesting water developments are an important resource in desert environments during hot, dry periods (Krausman et al. 2006, Lynn et al. 2006).

Among birds, variation in seasonal water use (greater in spring when compared with autumn) may be a response to changes in water content of food or greater need for water during the breeding season; thus, free-standing water has been hypothesized to affect the reproductive success of birds (Lynn et al. 2008). The black-throated sparrow (*Amphispiza bilineata*) is the only resident bird in North America known to survive without free-standing water, but frequently has been observed using water developments during autumn migration (Smyth and Bartholomew 1966, Lynn et al. 2008). Additionally, evidence from laboratory experiments indicated that black-throated sparrows produced significantly larger clutches when water was provided, suggesting that access to free-standing water increases productivity, and likely recruitment, in that species (Coe and Rotenberry 2003, Lynn et al. 2008).

Some chiropterans are dependent on free-standing water and many, if not all, species of bats probably require free-standing water on occasion (Rabe and Rosenstock 2005). Availability of surface water sources may limit distributions of bats in desert environments (Rabe and Rosenstock 2005), and water developments likely have expanded the distribution of bats, particularly in areas where suitable roosts are present (Geluso 1978, Rosenstock et al. 1999). Lactation imposes additional water demands on all mammals, and availability of free-standing water is probably most important to lactating chiropterans (Kurta et al. 1989, Rabe and Rosenstock 2005). Bats are strongly attracted to water sources in arid habitats, especially during the hottest and driest part of the summer, and they use water developments for drinking and to forage for insects (Rabe et al. 1998, Waldien and Hayes 2001, Rosenstock et al. 1999, Rabe and Rosenstock 2005, Tuttle et al. 2006). Additionally, bat species diversity and use at water developments have been positively correlated with surface area of open water (Rosenstock et al. 1999, Rabe and Rosenstock 2005). Managers interested in expanding distributions of bats should use larger catchments that have an open surface and minimize surrounding barriers, such as covers to reduce evaporation, which may impede flight around those water developments (Rabe and Rosenstock 2005, Tuttle et al. 2006).

Vegetation near wildlife water developments can be affected by livestock, which are known to concentrate in areas close to permanent water sources (deLeeuw et al. 2001). Changes in vegetation resulting from livestock grazing near water developments include broken soil crusts, unnatural levels of erosion, dominance of unpalatable plants, and decreases in palatable perennial grasses due to selective grazing (James et al. 1999). Thus, managers should consider exclusionary fencing to prevent livestock from concentrating near

water developments intended for wildlife to avoid damage to the surrounding vegetative community.

Water requirements often differ for introduced populations of ungulates, such as bighorn sheep, that are naïve to those landscapes where the introduction occurs (Smith et al. 1988, Wallach et al. 2007, Whiting et al. 2009). Introduced populations are likely to be dependent on water developments, particularly those associated with release sites, until they become familiar with landscapes around where the population was established, and availability of water likely affects success of those introductions (Smith et al. 1988, Wallach et al. 2007, Whiting et al. 2009). Location of permanent sources of water, such as water developments, in arid environments is an important consideration when evaluating potential areas for introductions (Singer et al. 2000a, 2000b), especially in habitats that are important for both males and females (Whiting et al. 2010).

WATER QUALITY

Another issue in the debate over wildlife water developments has been water quality. Indeed, quality of water available for use by wildlife is an important management consideration, and poor water quality could affect health of wildlife through physiological distress, electrolyte imbalances, or dehydration, as well as being potentially noxious or toxic (Broyles 1995). Biological factors most likely to affect water quality at natural or artificial sources are the result of high temperatures, high evaporation rates, contamination by feces or other organic matter, and infrequent flushing, most of which are of heightened concern during summer (Broyles 1995; Bleich 2003; Rosenstock et al. 2004, 2005; Bleich et al. 2006). Indeed, evaporation raises the ionic concentrations of already mineralized or saline waters. Biological contaminants (blue-green algae, bacteria, and invertebrates) can cause toxemia, diseases, or parasitism and transmission of parasites (Kubly 1990, Broyles 1995). Nevertheless, appropriate design and maintenance of water developments can assure availability of good-quality water (Rosenstock et al. 2004, 2005; Bleich et al. 2006).

A frequently cited example of water developments having posed a health risk to wildlife was reported by Swift et al. (2000), where ≥ 45 bighorn sheep died near two wildlife water developments. Swift et al. (2000) reported that toxin produced by *Clostridium botulinum* was most likely responsible for the mortality event, a result of contaminated water within the storage tanks, but their diagnosis was presumptive. Nevertheless, the condition and dispersion of carcasses indicated a rapid onset of mortality, typical of toxicity caused by ingestion of *C. botulinum* toxin. Conditions suitable for the production of *C. botulinum* toxin (i.e., anaerobic decomposition of organic material associated with warm temperatures) are not restricted to wildlife water developments, and likely occur more often at natural water sources used by bighorn sheep than previously had been recognized (Bleich 2003, Bleich et al. 2006).

Several investigators have assessed quality of water in wildlife water developments. Bleich et al. (2006) compared water quality among 3 types of water sources (water stored in natural tinajas [rock basins], aboveground in tanks constructed of metal or plastic, and underground in fiberglass tanks). A few differences in water-quality parameters were reported between the natural tinajas and the two different types of wildlife water developments (Bleich et al. 2006). Water quality in the catchments was within recommended guidelines for livestock, and observed differences were thought to be related to the design features of the developments (Bleich et al. 2006). Because guidelines for water quality have not

been published for wildlife, those guidelines available for livestock often are used as a surrogate (Bleich et al. 2006). Water quality also has been evaluated at natural, modified natural, and anthropogenic water developments, including natural tinajas, modified tinajas, springs, rainwater catchments, and wells (Rosenstock et al. 2004, 2005). The majority of constituents detected occurred at levels below recommended maxima for livestock, and those that occurred above recommended levels (pH, alkalinity, and fluoride) were presumed to be nontoxic to wildlife (Rosenstock et al. 2005). Additionally, no significant evidence of toxins produced by blue-green algae has been observed, and water developments do not appear to play a significant role in transmission of hemorrhagic disease viruses (Rosenstock et al. 2004, 2005).

Although specific water quality guidelines for wildlife are lacking, results of investigations completed to date — with the exception of the accidental deaths reported by Swift et al. (2000) — do not support the hypothesis that water quality is problematic for wildlife that use anthropogenic water developments. Indeed, several investigators have concluded that water developments in desert environments do not constitute a health threat to wildlife (Rosenstock et al. 2004, 2005, Bleich et al. 2006). Situations in which specific elements or other parameters that do not meet guidelines for water quality of livestock may occur at some water developments, but studies to date suggest they rarely occur (Rosenstock et al. 2004, 2005; Bleich et al. 2006).

ENTRAPMENT AND MORTALITY

Water developments can present a risk of drowning by wildlife that become entrapped. The largest such mortality event documented involved 13 bighorn sheep that drowned in a water storage tank in the Mojave Desert, California (Swift et al. 2000). Such events are rare, but demonstrate the importance of the placement of holding tanks since the individuals that drowned were able to access the tops of the tanks. Because of that event, Swift et al. (2000:188) noted that, "...access to the tank tops by bighorn sheep can be prevented by placement of the guzzler tanks away from ledges or rocks" and a protective platform can be added to the top of storage tanks can prevent bighorn sheep from breaking through or causing the tank to collapse.

If entrapment within water developments was a common occurrence, animal remains should be regularly found within water developments. Desert tortoise (*Gopherus agassizii*), a species that cannot swim, has been studied extensively in regard to the risks of entrapment and drowning in water developments (Hoover 1996, Andrew et al. 2001, Rosenstock et al. 2004). Although Hoover (1996) reported the remains of desert tortoises in some "small game guzzlers," he could not determine the cause(s) of death. Further, the hypothesis that water developments for wildlife are a substantial source of mortality for desert tortoise has not been supported by the results of detailed investigations (Andrew et al. 2001, Rosenstock et al. 2004). Very few remains of tortoises have been reported in water developments, indicating that water developments do not present a significant risk to desert tortoise (Andrew et al. 2001, Rosenstock et al. 2004). Indeed, most skeletal remains recovered showed a high degree of breakage consistent with predation by mammals or birds of prey (Andrews 1990; Andrew et al. 2001), and Andrew et al. (2001) hypothesized that remains found in water developments likely came from scat deposited nearby, or pellets cast by birds of prey (Andrew et al. 2001). Moreover, quantification of faunal remains in

or near water sources is not a reliable index of predation or drowning events, and can only be determined by direct observation or necropsy (O'Brien et al. 2006). Although risks of entrapment have been reported to be insignificant, water developments are typically fitted with escape ramps to prevent drowning by wildlife that enters the water (Bleich et al. 2005).

PREDATOR-PREY RELATIONSHIPS

Water developments are used by a diverse array of species, including predators, but do not appear to present an increased risk of predation among animals that use them (Krausman et al. 2006). Because most animals are attracted to surface water, water developments have been suggested to be "predation traps" or "predation sinks" where visiting animals are likely to be ambushed by predators (Rosenstock et al. 1999, 2004; DeStefano et al. 2000). Until recently, interspecific relationships, such as predator-prey interactions, have gone largely unassessed at water catchments (Broyles 1995). Nevertheless, the literature contains references to predation at water developments in the form of observations of individual predation events, inferences based on use by predators, or discoveries of prey remains (Ballard et al. 1998, Rosenstock et al. 1999).

Predator observations and sign have been reported to be greater around water developments when compared to non-watered control sites (DeStefano et al. 2000, O'Brien et al. 2006). Smith and Henry (1985), however, reported no difference in predator use near water developments when compared to non-watered control plots. Little evidence exists to support the hypothesis that use of water developments by predators leads to increased rates of predation, and reports of increased predation around water developments appear to be largely unfounded (Rosenstock et al. 1999, 2004; DeStefano et al. 2000; O'Brien et al. 2006).

Instances of predators concentrating hunting activities around water sources in the United States have not been reported, or are scarce in the literature. O'Brien et al. (2006) recorded >5,000 visits by mammalian predators to water sources, but reported little evidence (4 predation events by bobcats [*Lynx rufus*]) to corroborate an increase in predation rates. Further, no avoidance of water sites by prey species because of predator visitations was reported (O'Brien et al. 2006). DeStefano et al. (2000) documented predator sign at water sites that was >7 times greater than at non-watered sites, but did not find evidence to support the claim that water developments increased predation rates. Thus, predators drink at surface sources when water is available, but they do not appear to use them as focal areas for hunting (DeStefano et al. 2000, O'Brien et al. 2006). Predation may occasionally occur at water sources, but we located no evidence that predation at water developments influences population dynamics of either predator or prey species.

Use of water developments by predators may result from a scarcity of free-standing water in surrounding areas, especially in arid environments (DeStefano et al. 2000). According to the ambush-habitat hypothesis, predators should spend more time and make more kills in habitats with greater cover (Pennycuick 1975, Maddock 1979). According to the prey-abundance hypothesis, predators should spend more time and make more kills in areas where their primary prey are at the highest densities (Pennycuick 1975, Maddock 1979). Grant et al. (2005) studied African lions (*Panthera leo*) and reported successful predation rates with respect to different habitats, including sources of surface water. Grant et al. (2005) concluded that lions selected fine-scale areas where prey species were easier to catch, rather than areas where prey densities were highest, such as at water sources, consistent with the

ambush-habitat hypothesis. Those authors indicated, however, that water availability was not a significant factor affecting their results, likely because of colinearity between river banks and associated vegetation.

Conversely, deBoer et al. (2010) examined predation rates by African lions in different habitats, and concluded that prey availability was more important than prey vulnerability, consistent with the prey-abundance hypothesis. Although lions were found near water sources frequently, lions could select water sources for other resources, such as shade or denning sites (Grant et al. 2005; deBoer et al. 2010). Senzota and Mthakko (1990) reported no difference between numbers of 3 species of large mammals killed near (<250 m), when compared to areas more distant (250 m - 500 m) from, an African water source. Thus, the addition of water developments, which usually results in more available surface water than under natural conditions, could dilute predator density around individual water sources (DeStefano et al. 2000). African lions are much larger, have different hunting strategies, and have more abundant prey than do mountain lions (*Puma concolor*), the primary predator of North American ungulates, which occur at low densities in the desert southwest (Bleich 2005). If water sources in Africa do not concentrate prey species or increase predation rates on terrestrial ungulates (Grant et al. 2005, deBoer et al. 2010), it is unlikely that predation rates on ungulates around water developments in North American deserts (where predator densities are much lower) would increase as a result of the provision of water.

Although access to water may provide predictable locations for encountering prey, a successful predation event depends on a variety of factors including predator behavior, prey behavior, and the composition and cover of vegetation (Grant et al. 2005, deBoer et al. 2010). Water developments may alter the immediate area in some instances by increasing vegetation and hiding cover for predators if water seeps from catchments or developments that modify natural springs (Cutler and Morrison 1998, Valeix et al. 2008). As cover of vegetation increases, large prey modify their activity, group size, and drinking frequency, responses that likely are the result of increased predation risk; this effect likely is more prevalent near water sources in African ecosystems than in the arid regions of North America (Valeix et al. 2008; deBoer et al. 2010).

The value (or detriment) associated with vegetative cover differs among species of birds or mammals. Larsen et al. (2007) reported that chukar (*Alectoris chukar*) exhibited decreased use of water developments with increased canopy cover, presumably a response to perceived risk of predation. Small prey were sensitive to distance to vegetative cover, which may be an indication of vulnerability to predation when in open areas (Valeix et al. 2008). Lagomorphs preferred water catchments protected by vegetative cover, while some species of partridge preferred open water catchments lacking cover (Lacasa et al. 2009), and many species remain at water sources for only a few minutes (Lynn et al. 2006, Waddell et al. 2007). Bighorn sheep and mule deer, for example, generally remain at water sources <5 minutes (Rosenstock et al. 2004, Waddell et al. 2007, Cain et al. 2008b).

Rosenstock et al. (2004) observed altered behaviors and time spent in the vicinity of wildlife water developments when they were dry. Bobcats were observed entering the tank connected to an empty trough and remained in the vicinity up to 15 times longer than when water was present (Rosenstock et al. 2004). Mule deer were observed licking the empty trough, foraging nearby, and bedding next to the trough for up to 4 hours at a time, and remained in the vicinity up seven times longer than when water was present (Rosenstock et al. 2004). Mule deer that were denied access to traditional watering sites during summer in the Picacho Mountains in Arizona left the area and obtained water from outside their

established home ranges (Hervert and Krausman 1986). In addition, those female deer rapidly returned to their established home ranges after obtaining water (Hervert and Krausman 1986).

Some species of ungulates avoid water sites at night when predation is more likely to occur, likely indicating that prey species make temporal adjustments to avoid encountering predators during periods that coincide with hunting activities (Valeix et al. 2009). An absence of dense vegetation near water developments, short visitation times when water is present, and prey avoidance during periods of hunting activity, suggest that hunting efficiency of predators is not enhanced in the vicinity of those water sources (Grant et al. 2005, Valeix et al. 2008). Thus, predators likely accrue few, if any, benefits by hunting near functional water developments (Grant et al. 2005, Valeix et al. 2008). It is clear, however, that more research is needed to determine how vegetation density around water sources affects their use by predators and potential prey.

Avian predators, especially the common raven (*Corvus corax*), concentrating around water sources have been a concern in desert environments (Knight et al. 1993a, DeStefano 2000, Boarman 2003), particularly with respect to desert tortoise. An increase in common ravens throughout desert ecosystems has been correlated with anthropogenic developments, including water sources (Knight et al. 1993a, DeStefano 2000, Boarman et al. 2003). For example, ravens historically were uncommon in the Mojave Desert, but humans have provided food and roosting resources in otherwise uninhabitable environments, thereby increasing the distribution of those corvids (Knight et al. 1993a, Boarman 2006). In the Mojave Desert, there has been an astounding 1,000% increase in the number of ravens over the past three decades (Boarman 2003, Boarman et al. 2006). Some investigators have noted that anthropogenic resources led to increased survival rates and reproductive success of ravens, with >225 times the density of ravens found near areas with human developments than in open desert or rangeland habitats, areas where raven survival and reproductive success are poor (Knight et al. 1993a, Kristan and Boarman 2002, Boarman 2003, Boarman et al. 2006, Webb et al. 2009).

Raven populations are strongly influenced and associated with the development of roads and linear right-of-ways, urbanization, and agricultural land uses (Knight et al. 1993a, 1999; Kristan and Boarman 2002; Webb et al. 2009), all of which may be indirectly associated with presence of surface water or water developments. Roads are used to access some water developments, urbanization increases availability of free-standing water, and agricultural lands require water for crops or livestock (Knight et al. 1993a, 1993b; Knight et al. 1999; Boarman 2003; Boarman et al. 2006). Raven dispersal appears to be influenced by a combination of anthropogenic resources; thus, ravens would rarely be expected to travel away from urbanized areas into desert or rangeland habitats where those resources are scarce (Webb et al. 2009). Indeed, during almost 38,000 hours of video at wildlife water developments only 270 visits by ravens were reported, with a mean duration of <3 minutes per visit (O'Brien et al. 2006).

INTERSPECIFIC COMPETITION

Availability of surface water may increase the potential for competition between some native ungulates and non-native species such as feral ass (*Equus assinus*), feral horses (*Equus caballus*), and cattle (deLeeuw et al. 2001, Brown et al. 2010, Whiting et al. 2011), because native ungulates are naturally subordinate to larger species (Berger 1985). Further, the physical presence of livestock can influence the behavior of native ungulates (deLeeuw

et al. 2001, Stewart et al. 2002, Brown et al. 2010). For example, desert bighorn sheep and feral horses occur together in many arid regions of western North America (Ostermann-Kelm et al. 2008). The presence of feral horses at water sources reduced use by bighorn sheep, and caused bighorn sheep to abandon other water sources that were used by feral horses (Ostermann-Kelm et al. 2008). In addition, the presence of cattle can reduce the use of water sources by a variety of wildlife, suggesting livestock and human activities related to water sources had a negative effect on the distribution of wildlife (deLeeuw et al. 2001). Scott (1998) cautioned that wildlife water developments available to livestock could result in detrimental impacts to wildlife if such developments increased livestock use in a particular area, and that such impacts would be manifested primarily through competition for forage.

Although competition for forage between wildlife and exotic species or livestock around water developments has been a concern, few investigators have considered the potential for competition between native ungulates to be enhanced by such developments. Krausman and Leopold (1986) noted, however, that if wildlife water developments attracted mule deer to areas used by bighorn sheep a potential consequence would be an increase in use of available forage, with possible detrimental impacts to bighorn sheep. Krausman and Leopold (1986) urged caution in placing wildlife water developments for bighorn sheep to avoid competition and use of range resources by additional ungulate species. Access to wildlife water developments by feral or domestic livestock can be effectively eliminated through the construction of carefully designed fences (Brigham 1990, Andrew et al. 1997), but fences that allow passage of either mule deer or bighorn sheep, while excluding the other, have not been perfected. Finally, some investigators have cautioned that managers should consider the potential for wildlife to perceive an increased risk of predation associated with fenced developments (Larsen et al. 2007, 2011).

Life forms other than vertebrates could also be competitors for water. Use of water by honey bees (*Apis mellifera*) is frequently encountered and commonplace among natural and anthropogenic water sources in desert environments (V. C. Bleich, California Department of Fish and Game, unpublished data). Rabe et al. (2005) reported that honey bees were widespread in the Sonoran Desert of Arizona, and occurred at all of the 54 wildlife water developments they sampled. Similarly, Boyce et al. (2002, 2003) reported the presence of feral honey bees at several wildlife water developments in the Sonoran Desert. Honey bees have the potential to decrease the effectiveness of wildlife water developments by directly competing for water intended to benefit other species, including bighorn sheep (Boyce et al. 2003).

There is evidence that the presence of honey bees also has indirect consequences for use of water by ungulates. Indeed, Boyce et al. (2003) noted that bighorn sheep spent more time at wildlife water developments when their visits were interrupted by feral honey bees than when such visits were not interrupted and, as a result, bighorn sheep demonstrated behavioral responses (violent head shaking, rapid withdrawal from the water source, and temporary refusal to drink); such responses could have implications for energy expenditure and predation risk, and could alter patterns of visitation. Thus, honey bees have the potential to compete directly and indirectly (through interference) for an important resource that wildlife water developments are intended to enhance. The extent to which such competition could affect availability of water to other species has not been investigated in detail, although O'Brien et al. (2006) reported no evidence of interference during >38,000 hours of video surveillance.

Bees collected from water developments in the Sonoran Desert of Arizona

(Rabe et al. 2005) or California (Boyce et al. 2002) commonly exhibited African mtDNA, indicating they were hybrids (*A. m. scutellata* x *A. m. ssp.*), but bees collected at two wildlife water developments in the Mojave Desert of California did not possess African mtDNA. Africanized honey bees are extremely aggressive, and could present a threat to any approaching animal; nevertheless, Boyce et al. (2003) speculated that free-ranging bighorn sheep would have no difficulty escaping to a safe distance from a disturbed colony. Presumably, other ungulates also would have that advantage.

DISCUSSION

Free-standing water is assumed to be one of the primary factors limiting the distribution, productivity, or recruitment of many species of desert wildlife. Thus, wildlife management agencies have invested significant resources in construction and maintenance of water developments (Rosenstock et al. 1999, Cain et al. 2006). Enhanced distribution, abundance, survival and fitness of wildlife have been goals of managers implementing water developments since the 1940s, but the potential for negative effects has created controversy about the efficacy of those structures. Although many studies have implied greater conservation benefits from catchments than previously recognized (Krausman et al. 2006), use of free-standing water and water developments by wildlife could be opportunistic, and use of a resource does not necessarily indicate a requirement for that resource (O'Brien et al. 2006).

Quality of water in catchments has been brought up because of the potential to harbor water-borne pathogens or blue-green algae, both of which can lead to mortality among wildlife (Broyles 1995, Swift et al. 2000, Rosenstock et al. 1999). Animals occasionally become trapped in water developments (Swift et al. 2000), predation attempts at or near water developments have been documented (Rosenstock et al. 1999, 2004; DeStefano et al. 2000), and some investigators (Broyles 1995, Cain et al. 2008b) have suggested that not all water developments yield desired benefits. Nonetheless, negative effects purportedly associated with water developments are not supported by available data and remain highly speculative (Rosenstock et al. 1999, Cain et al. 2008b).

In contrast, many investigators have reported that water developments have been beneficial to a variety of game species including ungulates and game birds (Rosenstock et al. 1999, 2004; Morgart et al. 2005; O'Brien et al. 2006). Moreover, a diverse array of non-game species have also been reported to benefit from water developments, including resident and migratory birds (Lynn et al. 2006, O'Brien et al. 2006), resident and migratory bats (Rosenstock et al. 1999, 2004; Rabe and Rosenstock 2005; Tuttle et al. 2006; O'Brien et al. 2006), kit fox (*Vulpes macrotis* — a species previously reported not to require free-standing water for survival) (Rosenstock et al. 1999, 2004), and a variety of other mammals, reptiles, and amphibians (Burkett and Thompson 1994, Rosenstock et al. 1999, 2004; Krausman et al. 2006; Lynn et al. 2006, 2008).

Although negative effects of water developments appear to be largely unsubstantiated, many positive effects of the provision of water for wildlife have been documented (Rosenstock et al. 1999, Krausman et al. 2006). Individuals of many game and non-game species have likely benefited, but not all water development projects have yielded expected increases in animal distributions or abundance (Rosenstock et al. 1999). Nevertheless, mammals increase their use of surface water during lactation (Cain et al. 2006), and water availability could have a positive influence on recruitment, although lactation is

energetically demanding and quality of available forage also has a limiting effect (Krausman et al. 2006, Lynn et al. 2006). Further, water developments could play an increasingly important role in the maintenance of metapopulation function (Bleich 2008, 2009), in offsetting effects of extended droughts or modifications to naturally available surface water (Longshore et al. 2009), or changes in composition of vegetation (Epps et al. 2004), all of which could occur as a result of long-term climate change (Dolan 2006).

To truly understand the effects of water developments, further work is needed to correlate water development with growth and expansion of species ranges, survival, reproduction, and health, as well as predator-prey relationships. The results of our review are consistent with the conclusions of Ballard et al. (1998), and confirm that the professional literature as yet fails to substantiate claims that water developments are detrimental to the wildlife populations they are intended to benefit. Nevertheless, future studies should investigate the water requirements of species in arid environments to determine if access to free-standing water meets intended goals of increased distribution, productivity, recruitment, or survival of those species that were intended beneficiaries. Effects of provision of water on performance of populations, particularly the link to fitness through increased productivity and recruitment, has not yet been documented. Further, if there is an increase in distribution, productivity, or recruitment, how those changes influence the health of individuals and overall populations is of interest to wildlife managers.

Long-term studies over multiple years — including those with drought or higher than average precipitation — and with strong experimental designs (control, replication, and treatments) are needed to fully understand the influences of water developments on population performance (Ballard et al. 1998, Brown 1998). We realize investigations of links between fitness of populations and access to free-standing water can be difficult to implement and complete because of environmental stochasticity, length of time, and the large amount of funding required (Cain et al. 2008b); however, those data are needed to understand the effects of water developments on populations. Managers must implement repeatable, experimental manipulations to further elucidate the benefits or detriments of water developments for wildlife (deVos et al. 1998).

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