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Chapter 11

Amphibian Road Mortality and How to Prevent It: A Review

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Abstract — Mortality of amphibians on roads is a problem from an animal welfare and conservation perspective. We review methods to reduce road mortality of amphibians that have been used since the early 1970s in European countries, mainly Austria, Germany, and Switzerland, and we discuss advantages and disadvantages of these methods. No method works best for all species and situations. Although most methods work well for anurans on their way to breeding sites, they are substantially less efficient for juveniles and *Triturus* newts. Underpasses ("toad tunnels") are a common technical solution to prevent amphibian road mortality. We present details on the construction of tunnels and associated barrier walls. We also suggest measures to evaluate the efficiency of tunnels and barrier walls. The prevention of road mortality is the first goal, but from a conservation perspective long-term population viability is the more important goal. We conclude by suggesting several areas for future research, namely the use of underpasses by juveniles and newts.

Key words — Amphibian, Anuran, Drift Fence, Ecopassage, Effectiveness Assessment, Evidence-based Conservation, Juvenile, Newt, Population Viability, Road, Traffic, Toad Tunnel, Underpass

Roads and traffic have major impacts on animal populations and communities (Stoner 1925; Trombulak and Frissell 2000; Forman et al. 2003). The negative effects of roads and traffic on amphibian populations have been noted for a long time (e.g., Van Gelder 1973). The first extinction of an amphibian population attributed to road mortality dates back to at least the 1950s: a population of common toads (*Bufo bufo*) declined from about 500 in 1950 to extinction 10 yrs later (H. J. Moore, pers. comm., as cited by Heusser 1968). Not surprisingly, ever since amphibian road mortality became an issue, conservationists invented methods to reduce road mortality of amphibians (e.g., Meisterhans and Heusser 1970) and conservation biologists began to study the impacts of roads and road mortality on amphibian populations (e.g., Heine 1987; Fahrig et al. 1995; Hels and Buchwald 2001; Andrews et al. 2008).

Our goal is to provide a technical review of methods to reduce amphibian road mortality based on 30 yrs of experience in Switzerland and neighboring countries (Grossenbacher 1981; Ryser 1988, 1989; Zumbach 2002). Excellent reviews of methods and their efficiency to prevent amphibian road mortality include Langton (1989), Laufer (1997), Frey and Niederstrasser (2000), and Glandt et al. (2003). We do not attempt to provide a comprehensive review; our goal is to present and discuss the efficiency of the most common methods currently used. Much of the information that we review is based on knowledge accumulated since 1979 at KARCH, the Swiss Amphibian and Reptile Conservation Program (http://www.karch.ch/; accessed 29 February 2008). We synthesize a lot of "gray" literature, mostly unpublished reports by ecological consultants prepared for governmental conservation agencies and personal communications by conservationists and ecological consultants who have studied the road ecology of amphibians. The review is therefore biased towards our own experience. Much of the knowledge available is anecdotal. It would be worthwhile synthesizing the knowledge in an evidence-based conservation manner (Pullin and Knight 2001; Sutherland et al. 2004).

We first present some data that show the extent of the problem of amphibian road mortality. We then briefly describe dif-

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ferent common methods to prevent amphibian road mortality and discuss their pros and cons. This part of the review is technical and deals with conservation engineering rather than conservation biology. Finally, we discuss how to evaluate the effectiveness and success of these methods. When we discuss amphibian road mortality and methods to reduce it, we focus on road mortality associated with the directed migration of reproductive adults from their hibernation sites to breeding ponds and back from the ponds to summer habitats. These migrations often appear to follow rather narrow corridors such that the width of the migration front may be only a few hundred meters and the stretch of road where mortality occurs is quite short. In Europe, these breeding migrations primarily involve Common Frogs (*Rana temporaria*), Common Toads (*Bufo bufo*) and *Triturus* newts. There are, of course, other instances where amphibian road mortality occurs (e.g., the much less conspicuous breeding migrations of the salamander *Salamandra salamandra* or during dispersal between populations, i.e., the effects of roads on connectivity) but these are not the focus of the review.

Roads and Their Impacts on Amphibians: The Scale of the Problem

Data from Switzerland may serve to illustrate the high density of road networks and the pervasiveness of amphibian road mortality. Almost a third of Switzerland (30.3%) is covered by forest or scrubland, 38.3% is used for agricultural purposes, 5.9% is covered by built-up areas (including transportation infrastructure), 4.2% by lakes and rivers, and the remaining 21.3% by unproductive land (BUWAL, ARE, BAV, and ASTRA 2001). Switzerland is divided into three main landscapes: Jura, Central Plateau and Alps (where most of the unproductive land is found).

The federal road network (mostly highways) had a total length of 1,638 km in 1999. In 1996, the state road network comprised 18,238 km and that of the communes 51,197 km, with about an additional 40,000 km of private roads. This gives a total road length of more than 111,000 km (BUWAL, ARE, BAV, and ASTRA 2001). As Switzerland has a surface area of 41,285 km^2, road density is approximately 2.7 km per km^2 of national territory. If only the Central Plateau is considered (where most humans and amphibians live), the density is even higher (3 to 4 km per km^2). In addition, and not included in these calculations, there are about 29,000 km of forest roads with low traffic volumes. The car ownership rate in Switzerland is high, with 613 vehicles per 1,000 inhabitants (7.1 million inhabitants using 4.35 million vehicles; BUWAL, ARE, BAV, and ASTRA 2001). This suggests that on average there are about 40 cars per km of road (or about 100 cars per km^2), although most cars are found in the large cities and their suburbs.

About 90% of the wetlands originally present in Switzerland have been drained (Imboden 1976). The KARCH amphibian distribution data base holds records of about 12,000 amphibian breeding sites, i.e., 0.3 amphibian breeding sites per km^2. Schmidt and Zumbach (2005) estimate that in Switzerland in 2004 there were about 7,600 breeding sites of *Rana temporaria*, 3,800 breeding sites of *Bufo bufo*, and 5,400 breeding sites of *Triturus alpestris*, the most common newt.

Obviously, such a dense network of roads strongly affects amphibian populations. KARCH has records of 958 sites of road-amphibian conflicts but the suspected number of cases has to be much higher because many cases are not reported. We suspect that several millions of amphibians are at risk from traffic mortality. No action to prevent amphibian road mortality is made at 351 breeding sites, and KARCH has no information about conservation action at another 179 sites. Roads are temporarily blocked at 14 sites. Temporary drift fences are set up each spring at 269 sites whereas 125 sites have amphibian underpasses and permanent barrier walls. Mitigation ponds have been built at 20 sites (Zumbach 2002).

KARCH regularly receives data from 50 to 100 sites where conservationists are active. The average number of rescued amphibians per site is 1,800 with a maximum near 11,000. If there are fewer than about 100 amphibians rescued, conservation action is usually halted. We estimated that about 730,000 amphibians are protected from the risk of road mortality every year, mostly by volunteers (Zumbach 2002).

Traffic is generally considered the most important source of amphibian road mortality. There is another source of road mortality, however, that can be important: mortality resulting from sewage systems. In urban areas, large numbers of amphibians fall into drains (Ryser 1990) or enter sewers when searching for a humid refuge (Ratzel 1993). We do not further discuss this source of mortality but refer to a number of publications and reports on the topic (Kaplan 1990; Ryser 1990; Zumbach 1995; KARCH and Baudepartement des Kantons Aargau 1996). Another topic we do not deal with is amphibian mortality resulting from railways. Even though experts discern a problem with railways (BUWAL, ARE, BAV, and ASTRA 2001), there is almost no information on the topic (see Etienne et al. 2003 for a review).

Methods to Prevent Amphibian Road Mortality

At many sites, there are no efforts to reduce amphibian road mortality. This often happens if few amphibians are killed or if it is too difficult to prevent road mortality. There are three main causes. First, the road where amphibians are killed may be far from a village and no volunteers are available. Second, the road follows a lake shore and the section of road crossed by amphibians is very long. In such cases, building efficient systems of underpasses would be difficult and very expensive. Third, the breeding site is in a suburban or urban area where a dense network of roads makes efficient conservation action impossible.

We first review temporary solutions to prevent amphibian road mortality. Pictures, diagrams and plans of many methods that we discuss can be found on the internet site describing the report of Frey and Niederstrasser (2000). All temporary solutions focus on the migration of adults to breeding ponds, and no protection is expended for movements to terrestrial summer habitat or emigrating metamorphs. Typically, protective measures need to be set up anew every spring. Although conservation action may be implemented for a period of time, it may stop after a few years when volunteers are no longer available.

Road Signs — Road signs can be used to indicate that amphibians are crossing a road and request car drivers to drive carefully and slowly. Generally, this does not reduce road mortality effectively. However, if volunteers are carrying amphibians across the road, a road sign may be vital to increase the safety of volunteers.

Reduce Speed — Hummel (2001) argues that many amphibians are not only killed by the wheels of a car but also by the rapid change in air pressure if the amphibian is under a fast moving car. The argument is that there is high air pressure in front of the car and low air pressure under the car. So, an amphibian is first compressed by high air pressure and only in a fraction of second later the animal is inflated by low pressure. This rapid change is thought to make the lungs collapse. This mechanism is thought to operate if the speed of the car is greater than 30 km/h. Although the argument sounds reasonable, there are no studies that have verified the process. Heine (1987) and Hels and Buchwald (2001) state that the mechanism suggested by Hummel (2001) does not occur.

Temporary Drift Fences — Temporary drift fences have been used for a long time (Meisterhans and Heusser 1970). The method involves setting up a drift fence with pitfall traps that are usually spaced 15–20 m apart. Volunteers empty the traps usually in the evening and/or morning and release the amphibians on the other side of the road. If the drift fence is well constructed, this method can be highly effective and may be the best method for *Triturus* newts. A large number of different types of drift fences are now commercially available (Frey and Niederstrasser 2000). Wire netting fences are unsuitable because amphibians attempt to climb structures made of this material. An opaque plastic fence appears more efficient in reducing trespass rates and also facilitates amphibian movement along the fence into pitfall traps.

Temporary drift fences have three main disadvantages. First, the installation and daily checking of pitfall traps and drift fences requires a lot of work and many volunteers. Second, because traps and drift fences are usually checked at dusk when anuran migration has its daily peak and when most commuters return home, traffic can pose a risk to volunteers on the road (traffic is high and drivers can be tired and aggressive). Third, temporary drift fences protect only the spring migration of adults towards the pond; neither the return migration of adults nor the dispersal of juveniles into terrestrial habitat benefit from this conservation action.

In Switzerland, many volunteer groups have used temporary drift fences along roads for decades. The time series based on the numbers of amphibians captured at drift fences shows that this method works well. Furthermore, population declines induced by road mortality can be prevented even in the presence of some level of adult and juvenile road mortality as long as the quality of the amphibian breeding site and the terrestrial habitat remain unchanged (e.g., Maddalena et al. 2002).

An important advantage of temporary drift fences is their educational effect on volunteers, who also often take care of the breeding site itself. If volunteers take records carefully and report them to a central data base, the data can yield long time series of many populations even though population counts may vary in their precision. Such time series may be used to analyze large-scale population dynamics, population trends and breeding phenology (e.g., Houlahan et al. 2000). Volunteers may also collect data on the spatial pattern of the breeding migration. Such data are usually crucial when planning permanent systems, such as underpasses. In fact, KARCH recommends that two or three years of data should be collected before underpasses are planned and built.

Close Road to Traffic Temporarily — This method involves closing a road to traffic temporarily, usually during March and April each night ideally from 1700 to 0700. Although this method is the easiest by far, it is rarely used. Where the method is used, it works well. In many situations, however, roads are not closed to traffic because people are not willing to use alternative, longer routes.

Even if a road is temporarily closed to traffic, amphibian road mortality may still happen. If weather conditions are such that amphibians start to migrate early in the evening and before the road is closed to traffic, then significant mortality can occur. Nevertheless, we view closing a road to traffic temporarily as the most efficient method because it generally prevents road mortality and costs little. We are unaware of cases where a road was closed to traffic during summer to protect the migration of recently metamorphosed juveniles, although German regulations suggest closing roads to traffic also to prevent mortality of juveniles (Bundesministerium für Verkehr, Bau und Wohnungswesen 2000).

In the following sections, we describe methods to prevent amphibian road mortality which are permanently in place. These methods involve primarily offering new habitats and building underpasses.

Construction of a New Pond (Mitigation Pond) and Translocation of the Population — If no temporary or permanent technical solution is feasible, then a new pond at a safe place (i.e., where amphibians do not have to cross a road during their seasonal migrations) may be constructed. A mitigation pond serves to compensate for road mortality that cannot be prevented. This approach has not been used often because conservationists are reluctant to give up an existing breeding site. Whether constructing a new pond is a viable solution strongly depends of the value of the breeding site to be replaced. It may be easy to replace an artificial pond, e.g., an abandoned fish pond, but not possible to replace larger wetlands, such as marshes and fens. Also, it is not clear whether the new breeding site will be of the same quality and will be inhabited by the same species as the old breeding site. There are also political arguments against the construction of mitigation ponds. If people believe that ponds can easily be replaced, then there will be less political will to protect the original breeding site.

If new breeding sites are carefully constructed, they are usually colonized by amphibians (Oerter 1995). Because no good permanent technical solutions are known for *Triturus* newts, construction of a new pond is often the only sensible mitigation measure for road mortality, often in combination with a tunnel/barrier wall system.

In the cases we know, amphibians are allowed to colonize the new ponds naturally and populations are rarely actively translocated to new breeding sites because adults of many species show strong fidelity to the breeding site (Meisterhans and Heusser 1970; Reading et al. 1991). The success rate of translocations is a matter of debate (Schlupp and Podloucky 1994; Seigel and Dodd 2002; Edgar et al. 2005) and needs to be evaluated carefully, which may require monitoring adults and their reproductive success for several generations.

New Terrestrial Summer Habitat — In some cases it may be possible to reduce road mortality through offering suitable terrestrial habitat. This may only be possible for species such as *Alytes obstetricans* and *Triturus* newts whose terrestrial habitats are close to breeding sites. This method may be beneficial for the population simply because a larger proportion of the population uses terrestrial habitat that is not isolated by a road from the breeding site. It may also be possible to block access to terrestrial habitat on the other side of the road. This is achieved by installing a barrier wall between the breeding site and the road. This method is preferred when the terrestrial habitat is expected to disappear in the near future following urban development.

Remove the Road — Removing a road at sites with amphibian-road conflicts would be the best solution but is impossible for political reasons, at least in Switzerland. However, people are well aware of environmental issues and planners often redirect new roads away from wetlands or construct underpasses and ecopassages (e.g., Righetti 1997; BUWAL, ARE, BAV, and ASTRA 2001; Teufert et al. 2005).

Underpasses (Toad Tunnels) — Toad tunnels are probably the most well-known method used to reduce amphibian road mortality (Fig. 1). This method is preferred because road mortality is prevented both during migration to and from the breeding sites and during juvenile dispersal. However, experience shows that if underpasses and the associated barrier wall system are not well planned and constructed, then many amphibians, especially juveniles, will not use the underpasses. A series of reports documents the imperfect functioning of

Fig. 1. Photograph of an underpass and barrier wall system near Arcegno, Switzerland. The picture shows an entry to an open-top (ACO) tunnel and a metal barrier wall. The barrier wall has a zigzag shape. Note (i) the walking surface along the barrier wall and (ii) that the upper end of the barrier wall is ground level with the surface of the road. The wooden board helps to direct amphibians towards the tunnel entry. Photograph by Silvia Zumbach.

wildlife underpasses (e.g., Ramseier et al. 1996; Zangger and Fankhauser 1996; Häfliger and Wiprächtiger 2003; Schneeweiss et al. 2003).

Frey and Niederstrasser (2000) review the many different systems that have been used over the years. Many different designs of underpasses and barrier walls have worked well for a number of species (Langton 1989; Frey and Niederstrasser 2000; Bundesministerium für Verkehr, Bau und Wohnungswesen 2000; Glandt et al. 2003). It is important to note that a system of underpasses will only work in conjunction with a well constructed barrier wall; amphibians will not use tunnels without barrier walls. Kordges (2003) argues that in theory it would be straightforward to construct the perfect tunnel/barrier wall system (key elements are: large diameter of underpasses, underpasses should have natural soil rather than concrete as the underground, the barrier wall should be zigzag-shaped, and the connection between tunnel and barrier wall should be smooth; see Frey and Niederstrasser 2000) but that local constraints often prevent it. There are no standard solutions and in each case the systems need to be adapted to the spatial pattern of amphibian migrations, the species involved, and the local topography. Careful planning and construction are probably more important than the materials used because minor details may be decisive (Schneeweiss et al. 2003; Häfliger and Wiprächtiger 2003).

There are two main types of tunnels: one-way and two-way tunnels. A one-way tunnel is constructed such that amphibians fall into the tunnel and can leave the tunnel only at the other side of the road. To allow movement in both directions, two parallel tunnels must be constructed. The great benefit of this system is that the crossing rate is high because there is only one way out. The construction of these tunnels has proven difficult and many amphibians are unwilling to use these tunnels. This can lead to substantial mortality. Nowadays, the general consensus is that amphibians should not be forced to use tunnels. Hence, two-way tunnels are currently recommended in most European countries (BUWAL, ARE, BAV, and ASTRA 2001; Bundesministerium für Verkehr, Bau und Wohnungswesen 2000). The most favorable tunnels are those with a moist microclimate. Kyek and Wittmann (2004) recommend wildlife tunnels that are partially flooded; a small stream in the tunnel may also be favorable (Bundesministerium für Verkehr, Bau und Wohnungswesen 2000). The width of the stream should not cover the whole width of the underpass such that it can also be used by other small wildlife.

If there is no stream, then rectangular concrete tunnels with natural soil are best (Bundesministerium für Verkehr, Bau und Wohnungswesen 2000; Glandt et. al. 2003; John 2003). The recommended width of tunnels depends on the width of the road but all tunnels should be at least 1 m high and wide. If the road is wider than 50 m, then the width of the tunnel should be at least 2 m (Bundesministerium für Verkehr, Bau und Wohnungswesen 2000). Tunnels ought to be rectangular rather than round. If the edge between soil and lateral wall is concave rather than a 90 degree angle, amphibians will attempt to climb up the walls. This increases the time that amphibians need to cross the tunnel and reduces the probability that they will cross the tunnel at all.

Some companies (e.g., ACO Severin Ahlmann GmbH & Co KG, Rendsburg, Germany) produce tunnels that are open at the top. The "roof" of the tunnel is a grid and is flush with the road surface (Fig. 1). These tunnels were originally developed for draining rain water. These open-top tunnels do have some advantages and disadvantages in comparison with closed tunnels. The main advantage is the humid microclimate. Because the available tunnels are only 0.6 m deep (and, unfortunately, less than 1 m wide), they can be used in areas where the ground water table is near the surface. The disadvantage of the open-top tunnels is the change in air pressure in the tunnel caused by every passing vehicle, which may prevent amphibians from crossing the tunnel, and the entry of contaminated material from the road (e.g., road salt).

Tunnels should be built at least every 50 m because amphibians do not travel long distances along a barrier wall. If they do not find a tunnel within a short time, they will often return to the terrestrial summer habitat without breeding (Berthoud 1973; Zangger and Fankhauser 1996; Frey and Niederstrasser 2000).

Underpasses only work if there is a barrier wall (Figs. 1, 2). The barrier wall has two functions. First, it should prevent access of amphibians to the road. Second, it should direct migrating amphibians towards the tunnels. Barrier walls need to be built and maintained very carefully. The elements of the barrier wall must together form a smooth surface and there must be no gaps between individual elements of permanent barrier walls (Figs. 1, 2). Barrier walls can be made of concrete, metal, or UV-resistant polymers. Also, there must be no gaps between the barrier wall and the tunnels. If there is the slightest gap or anything else that might be used as a support

Fig. 2. Photograph of an underpass and barrier wall system near Porrentruy, Switzerland. The picture shows a concrete barrier wall, parallel to the road, made of L-shaped elements and the entry to a rectangular tunnel. Note (i) the walking surface along the barrier wall and (ii) that the upper end of the barrier wall is ground level with the surface of the road. The photograph was taken shortly after construction. Photograph by Silvia Zumbach

for climbing, amphibians will attempt to climb up, especially juveniles and *Triturus* newts. If this happens, the barrier wall does not direct amphibians effectively towards the tunnels and the efficiency of the system will be dramatically reduced. Gaps also occur where plants start to grow (Fig. 3), which greatly increases the effort for maintaining the barrier wall.

L-shaped elements are best for constructing the barrier wall because there is a smooth surface on which amphibians can easily move (Fig. 2), thus increasing movement speed and their use (Frey and Niederstrasser 2000). Again, if the edge between surface and lateral wall is concave rather than a 90 degree angle (Figs. 1, 2), amphibians will attempt to climb up the barrier wall. At the top, the L-shaped element should have an overhanging lip (Fig. 1) that prevents trespassing and which keeps the uppermost part of the fence dry such that newts and juveniles cannot use adhesion to climb. The height of the barrier wall is usually between 0.3 and 0.5 m and the

Fig. 3. Photograph of poorly maintained barrier wall. Some elements of the barrier wall are broken and overgrown by plants. Photograph by Silvia Zumbach.

width of the migration surface should be 0.3 m. Different amphibian species use the walking surface differentially. *Bufo bufo* usually hop along the barrier wall in close contact with the fence whereas *Rana temporaria* move further away from the fence (Glandt et al. 2003).

Unlike temporary drift fences, the upper end of the barrier wall should be ground level with the surface of the road (Figs. 1, 2). This permits amphibians and other animals to leave the road if they should get there; the barrier wall should not prevent amphibians from leaving the road, and amphibians should not get trapped on the road between the barrier walls on either side. For example, KARCH would not recommend a barrier wall as shown in Dodd et al. (2004).

If there is a lack of space, barrier walls are often built parallel to the road. They serve their function better, however, if they follow a zigzag line where tunnels are placed in the corners that face towards the road (Fig. 1).

Toad tunnels and barrier walls must be maintained carefully. Careful maintenance is as important as careful planning and construction. Before the start of the breeding season, the walking surface at the fence and the tunnels must be cleaned and adjacent grassy vegetation mowed. If elements are broken or if gaps have opened up, these need to be repaired (Fig. 3).

Ecopassages — Ecopassages ("green bridges") have been constructed for large wildlife such as mammals (Righetti 1997). They serve to increase connectivity between populations rather than connectivity between breeding site and summer/hibernation habitat (i.e., seasonal migrations) as discussed in this review. Nevertheless, Teufert et al. (2005) show that ecopassages may be used by amphibians.

Which Method Works Best? — In our opinion, underpasses are the best solution if only anurans are affected by road mortality and if the local topography allows the construction of a tunnel and barrier wall system as described above. We favor underpasses because all seasonal migrations, including juvenile migration, are protected against road mortality. If newts are involved, then a mitigation pond should be constructed because tunnels are often not used by newts. In many cases, a combination of methods works best.

There are often local constraints and therefore an optimal solution is not feasible. We believe that each case needs to be carefully evaluated and solutions need to be found that are suitable for local conditions and constraints, in terms of species and population sizes involved, topography, traffic density, availability of volunteers, and money. For example, if population sizes are small then the construction of relatively expensive underpasses may not be warranted.

Evaluating the Effectiveness of Underpasses and other Methods to Prevent Amphibian Road Mortality

The methods presented above help to reduce or even eliminate road mortality of amphibians. This is an important goal, especially from an animal welfare or ethical perspective. A conservation biologist might favor a different goal: Does conservation action enhance population viability in the long run? Given such a conservation perspective, one may accept road mortality of individuals as long as the population is not declining. However, if a substantial amount of money has been invested into constructing underpasses and a barrier wall, then road mortality may not be politically acceptable anymore. Thus, evaluating the effectiveness of methods to prevent amphibian road mortality has biological, economic, technical and political aspects. What has to be assessed depends on the conservation goals. Here, we focus on the biological aspects and on systems of toad tunnels with barrier walls. A comprehensive report on standard methods for assessing the effectiveness of permanent solutions is currently being prepared by a working group of German, Austrian, and Swiss herpetologists and should be available in 2009 (U. Geise pers. comm.).

Does the System Prevent Road Mortality? — This should be the first issue in assessing the efficiency of the system. A temporary drift fence or permanent wall can reduce road mortality to almost zero. However, zero road mortality should not be equated with population viability because a system that prevents road mortality may disrupt connectivity between the breeding site and the terrestrial habitat.

Although road mortality is easy to assess by counting the number of carcasses on the road, Hels and Buchwald (2001) highlight some of the difficulties with interpretation. For example, carcasses can be missed, especially if small newts and juveniles are involved, and carcasses may disappear quickly. If the goal is to prevent road mortality completely, then the assessment is relatively straightforward.

Does the System Facilitate Amphibian Crossing? — The next step in assessing the effectiveness (termed acceptance assessment in the German literature) is to investigate to what extent amphibians use the tunnels and how efficiently barrier walls direct amphibians towards the tunnels. At the most basic level, qualitative observations are made at the various elements of the system. For example, one may observe the end of the tunnels and check whether amphibians are leaving the tunnels. One may also observe the movement speed of amphibians at the barrier wall. This qualitative assessment, and all quantitative assessments (see below), should be made for (i) adults migrating towards the breeding site, (ii) adults returning from the breeding site, and (iii) for recently metamorphosed juveniles emigrating from the pond towards the terrestrial habitat. If multiple species are using the tunnel/barrier wall system, then assessments should be made for all species.

What Proportion of the Breeding Population should Use the Tunnels? — The next level of assessment is to make these observations in a quantitative way. It is not sufficient to count all individuals crossing the tunnels. The response variable to be measured is the proportion of the population ((i) to (iii) above) that arrives on one side of the tunnel/barrier wall system and that uses the tunnels successfully, i.e., leaves the tunnels safely and timely on the other side of the road. In other words, what proportion of the arriving individuals does not use the tunnels and return to the summer habitat without breeding? An example may illustrate the problem: If only 60% of the breeding population uses the tunnel/barrier wall system then it may be better to accept 30% of road mortality because a larger proportion of the population arrives at the breeding site. It is difficult to determine what proportion of the population should use the tunnels and breed: 100% would be ideal, but probably unrealistic. A lower proportion may suffice for demographic reasons, especially if density dependence in the larval stage is strong (Vonesh and De la Cruz 2002). From a genetics perspective, a larger number may be better, especially when considering that genetic effective population sizes are very small anyway (Scribner et al. 1997).

Ideally, a quantitative assessment would estimate the number of individuals arriving at the barrier wall, the number of animals arriving at the entrance of the tunnels, and the number of animals leaving the tunnels at the other side for both adults and juveniles and for all species. Such data may help to evaluate which parts of the system work well and which parts need improvement.

One approach to quantify these numbers and proportions is to set up a temporary drift fence parallel to the barrier wall at a distance of 50 to 100 m (U. Geise et al., pers. comm.). Amphibians are caught and counted at the drift fence, released on the other side, and allowed to continue towards the tunnels/barrier walls and the breeding site. Additional traps are placed at the exit of the tunnels. The drift fence allows quantifying the number of individuals that arrives at the barrier wall whereas the traps at the end of the tunnels allow quantifying the proportion of individuals that used the tunnels successfully.

The quality of the data and inference could be improved if individuals are marked, although financial constraints may prevent individual marking in many cases. Marking, of course, should not have adverse effects on the amphibians and should not bias the results. However, bias should be viewed in relation to the precision of the estimates (Schmidt et al. 2002). If two different marking methods are applied at the same time, then it may be possible to learn about the magnitude of bias. Overall, the benefits of marking may outweigh the drawbacks. Marking may allow tracking the movements of individuals which may yield valuable insights into how amphibians behave at the barrier wall, e.g., to what extent they move laterally along the drift fence. Individual marking may also allow estimating the time that individuals arrive at the other side. It is generally believed that a lower proportion of the breeding population successfully uses the tunnels if the time needed to cross the tunnels is long. This relationship, unfortunately, has never been quantified. If individuals are captured and marked at the drift fence, the barrier wall, the end of the tunnel, and at the breeding site, then it may be possible to use mark-recapture methods to analyze the data. Under such a scenario and assuming that natural mortality during the breeding migration is negligible, a simple survival analysis (Williams et al. 2002) would yield indirect estimates of tunnel use probabilities. One might also design a capture-recapture study where amphibians are captured at the tunnel/barrier walls, the breeding site, and in the terrestrial habitat. Such a study, conducted over multiple years, would allow a complete assessment of the effects of the tunnels/barrier wall on the demography and behavior of individuals. Additionally, these estimates would have standard errors and account for variable detection probabilities, which would further increase confidence in the results (Schmidt 2004).

How Does the System Affect Population Viability? — The reduction of road mortality should only be an initial goal of applying any method described above. The ultimate goal must be to enhance population viability. This is why we have stressed the importance of knowing the proportion of juveniles and breeding adults that successfully use a tunnel/barrier wall system. If the tunnel/barrier wall system disrupts connectivity between breeding sites and terrestrial habitat, then it may be detrimental to the viability of the population (Jaeger and Fahrig 2004). Thus, one may decide to measure population viability directly rather than assessing the functionality of the system. However, when a tunnel/barrier wall system is built, most authorities will want to test its effectiveness rather than population viability. Unfortunately, in most cases authorities demand no effectiveness assessment at all.

Population viability could be assessed through monitoring the dynamics of the population at the breeding site. Given the strong fluctuations in the size of amphibian populations (e.g., Meyer et al. 1998), this requires multiple years of monitoring, and, if available, information about population dynamics before the system was built. A conclusion of a population viability assessment may be that the system does not enhance viability. In this case, a necessary next step should consist of identifying problems and trying to find solutions. A poorly constructed tunnel and barrier wall system may be the only reason why a population is not viable. Changes in the quality of the breeding site also need to be considered.

Critical Knowledge That Is Currently Lacking

There are still gaps in our knowledge that impede our ability to develop better methods for the prevention of amphibian road mortality. Generally, we need more thorough quantitative and experimental studies (Dexel and Kneitz 1987) as only experiments can reveal cause-effect relationships. Ideally, such studies would be embedded in an adaptive management framework.

Juveniles — A number of recent population models suggests that the survival of juveniles is of fundamental importance for the persistence of amphibian populations (Lampo and De Leo 1998; Biek et al. 2002; Hels and Nachman 2002; Vonesh and De la Cruz 2002; Conroy and Brook 2003). Juveniles are difficult to mark and study, hence the available knowledge is scant. However, some studies have recently focused on the migratory behavior of juvenile amphibians (e.g., Malmgren 2002; Rothermel 2004; Schneeweiss et al. 2003; Stevens et al. 2004). Recent advances in mark-recapture theory allow estimating recruitment from data on adults only (Nichols et al. 2000). Such estimates of recruitment may provide sufficient insight into the use of a system by juveniles.

Newts — Some reports indicate that newts may desiccate in tunnels (John 2003; Häfliger and Wiprächtiger 2003). We are unaware of any studies that show that tunnel/barrier wall systems are used in a satisfactory way by newts. Construction of mitigation ponds far away from a road where suitable terrestrial habitat is available is the method that works if newt road mortality is high. A new pond will not reduce road mortality, but may compensate for losses.

What Proportion of the Breeding Population Should Use the Tunnels? — To determine the proportion of the breeding population that must use the tunnels for the population to remain stationary, future population models ought to address this question more explicitly than existing ones (Biek et al. 2002; Hels and Nachman 2002; Reyer et al. 2004). Conceptually, the problem is similar to the sustainable harvest of populations and methodological approaches to estimate sustainable levels of road mortality may be found in the wildlife literature (Williams et al. 2002).

Other Issues — Two issues require further research: microclimate and magnetoreception. The microclimate within the tunnels and along the barrier wall or temporary drift fence may be decisive (John 2003; Kyek and Wittmann 2004). Magnetoreception by amphibians may be affected by metal and the metal contained in concrete (Sinsch 1991; Philipps and Borland 1992; Diego-Rasilla 2003). Whether metal affects the efficiency of tunnels/barrier walls has not yet been studied.

Towards Evidence-Based Conservation — Assessing the effectiveness of underpasses and related methods to prevent road mortality would be an excellent candidate for building an evidence-based conservation framework (Pullin and Knight 2001; Sutherland et al. 2004). Because the effectiveness of any system is very likely to depend on local conditions, it may not be possible to generalize. For this reason, an evidence-based conservation framework, where information from many anecdotal, qualitative, and quantitative studies is summarized in a systematic way would be worthwhile. Although we have learned a lot over the past decades, there is still a need to learn more about reducing amphibian road mortality and improve our toolbox for amphibian conservation.

Useful Web Address

The comprehensive study by Frey and Niederstrasser (2000) is also available online:

http://www.xfaweb.baden-wuerttemberg.de/nafaweb/berichte/pas_03/pas3.html (accessed 17 March 2008). Although this report is written in German, it contains many drawings and pictures ("Abbildungsverzeichnis") that should be useful for most readers.

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