**Prepared in cooperation with the U.S. Fish and Wildlife Service**

# Road Impacts on the Baca National Wildlife Refuge, Colorado, with Emphasis on Effects to Surface- and Shallow Ground-Water Hydrology—A Literature Review

By Douglas C. Andersen

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Cover: Examples of unimproved (left) and improved (right) roads on the Baca National Wildlife Refuge.
All images in the document are of roads on the Baca National Wildlife Refuge taken by the author in January or June 2006 unless noted otherwise.

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# Conversion Factors

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| hectare (ha) | 2.471 | acre |
| square kilometer ($km^2$) | 247.1 | acre |
| hectare (ha) | 0.003861 | square mile ($mi^2$) |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

# Road Impacts on the Baca National Wildlife Refuge, Colorado, with Emphasis on Effects to Surface- and Shallow Ground-Water Hydrology—A Literature Review

By Douglas C. Andersen[1]

## Abstract

A review of published research on unpaved road effects on surface-water and shallow ground-water hydrology was undertaken to assist the Baca National Wildlife Refuge, Colorado, in understanding factors potentially influencing refuge ecology. Few studies were found that addressed hydrological effects of roads on a comparable area of shallow slope in a semiarid region. No study dealt with road effects on surface- and ground-water supplies to ephemeral wetlands, which on the refuge are sustained by seasonal snowmelt in neighboring mountains. Road surfaces increase runoff, reduce infiltration, and serve as a sediment source. Roadbeds can interfere with normal surface- and ground-water flows and thereby influence the quantity, timing, and duration of water movement both across landscapes and through the soil. Hydrologic effects can be localized near the road as well as widespread and distant. The number, arrangement, and effectiveness of road-drainage structures (culverts and other devices) largely determine the level of hydrologic alteration produced by a road. Undesirable changes to natural hydrologic patterns can be minimized by considering potential impacts during road design, construction, and maintenance. Road removal as a means to restore desirable hydrologic conditions to landscapes adversely affected by roads has yet to be rigorously evaluated.

## Introduction

The 37,400 ha Baca National Wildlife Refuge (NWR) in southern Colorado contains 14,200 ha of wetland, wet-meadow, and riparian habitat sustained primarily by surface flows in seven creeks draining the Sangre de Cristo Mountains. These creeks, which run more-or-less parallel to one another, enter the refuge on its eastern border and terminate within the refuge at or above a series of ephemeral playa lakes that line the margins of Saguache and San Luis creeks on the refuge's western border (fig. 1). The remainder of the refuge is primarily desert shrubland and grassland, supported by an average annual precipitation of about 20 cm, most of which (approximately 45 percent) falls as rain during July, August, and September (based on averages of values for Monte Vista, Saguache, Crestone 1SE, and San Luis Lakes 3W meteorological stations; data available on the Web at *http://www.wrcc.dri.edu*). Historic water management on what are now refuge lands included diverting flows out of creeks during spring runoff in order to flood irrigate 6,500 ha of meadows managed for wild hay production. This water management practice is being maintained by refuge staff. Thus, three hydrologic factors are major

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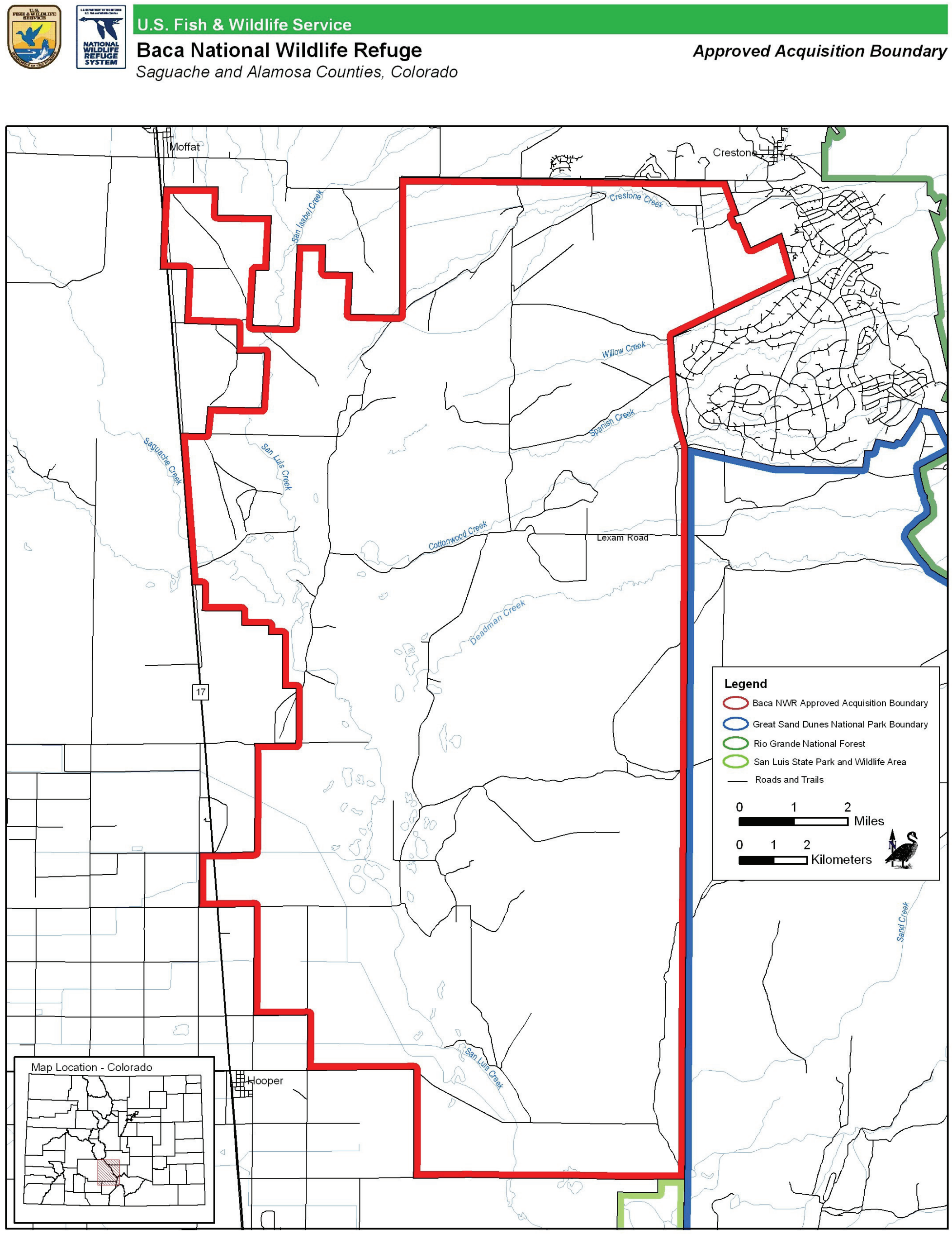


**Figure 1.** Map showing the approved acquisition boundary of the Baca National Wildlife Refuge, Colorado, and the location of the Lexam Road and various other roads. Most Closed Basin Project roads are not shown.

determinants of ecosystem structure and functioning on the Baca NWR: (1) soil-moisture levels during the growing season, (2) the character of the flow regime in natural (creek) channels (that is, the magnitude, frequency, timing, duration, and rate of change of flows), and (3) the amount and quality of water reaching the terminal playas.

The refuge also contains a network of unpaved roads, developed at various times and constructed in various ways. Many of these roads trend north-south and intersect the east-west trending watercourses (fig. 1). Understanding the effects of roads on the processes of surface-water flow and sediment transport in natural channels—how and to what extent roads have altered the natural flow regime and sediment transport processes—is key to understanding the effects of roads on the ecology of the Baca NWR.

This literature review was undertaken to catalog the potential effects of refuge roads on the natural and managed hydrological processes that produce the unique set of wetland and moist-meadow habitats and ecological relationships found on the Baca NWR. Understanding the potential effects is a necessary step in planning research to document actual effects. The review begins with an overview of road effects on ecosystems in general and progressively narrows to address issues likely to be specific to refuge landscapes. The review has been organized around the following questions:

1. *In what ways can roads affect an ecosystem's structure and functioning?*
2. *Are there particular problems or concerns associated with unpaved roads?*
3. *Are there special concerns associated with unpaved roads in semiarid and arid landscapes?*
4. *In what ways can roads affect hydrology on the Baca NWR?*
5. *Are effects on hydrology localized near roads or can they be widely distributed on the landscape?*
6. *Can rare hydrologic events (intense storms, droughts, and so forth) lead to new or magnified road effects?*
7. *How can road effects on natural hydrology be minimized?*
8. *What are the ecological costs and benefits of road removal?*

These questions are somewhat hierarchical in nature, and to minimize redundancy, the sections should be read sequentially and not treated as independent of one another. A brief glossary of terms associated with ecosystems, landscapes, hydrology, and road construction that are used in the text is provided at the end of the review. The literature review is a product of the U.S. Geological Survey Rapid Response Project titled "Preliminary assessment of the effects of roads on surface water and shallow ground water hydrology within the Baca National Wildlife Refuge," and was prepared in cooperation with the U.S. Fish and Wildlife Service.

The search for peer-reviewed scientific papers was conducted primarily in the CSA Illumina (Natural Sciences) database and the ISI Web of Knowledge database (products searched = Web of Science; Current Contents Connect; BIOSIS Previews; Zoological Record) in autumn 2005. Initially, all available years were searched using combinations of keywords, including (* indicates wildcard character) arid, Closed Basin Project, dust, ecolog*, effect*, endorheic drainage basin, groundwater, hydrolog*, particulate*, playa, road*, saline, San Luis Valley, sand, sand sheet, sediment*, semiarid, semi-arid, shallow groundwater, soil, and terminal lake. The review is not exhaustive in the sense that no attempt was made to obtain and review all of the primary literature available, even on the narrow topic of road effects on hydrology. Rather, the review focuses on all the literature that was considered to be directly pertinent to the Baca NWR.

## Past Reviews and Annotated Bibliographies

Several extensive reviews or annotated bibliographies were found on the Web. These are listed here by sponsor (table 1), but the completeness of the bibliographies and quality of the annotation was not investigated formally. The bibliography sponsored by the Grand Canyon Trust (Brown and others, 2001) initially appeared most pertinent for understanding the ecological impacts of roads on the Baca NWR because it focused on a nearby semiarid and arid region. The compilers state in their five-page executive summary that they gleaned more than 200 articles about road impacts to northern Arizona organisms and environments from the more than 6,000 publications then available describing the effects of roads. Nevertheless, most of the 14 references in their two-paragraph review of effects on hydrology, soil structure, and erosion refer to studies in coastal forests of Washington, Oregon, northern California, or the Appalachian Mountains. None deal with desert environments.

The Wildlands CPR website offers a searchable bibliography dealing with off-road vehicle (ORV) and road effects on the environment, with an emphasis on public lands and documents such as Environmental Impact Statements. The organization claims to be maintaining and updating the bibliography, which contained 12,000 references as of August 2005. Three searches undertaken by combining “hydrology” with “arid,” “semiarid,” and “desert” each returned only four entries. The other bibliographies found on the Web deal entirely or partially with mesic landscapes, and focus on roads used in silviculture.

**Table 1.** Bibliographies and reviews concerning ecological effects of roads that have been published on the World Wide Web.

| Sponsor | Author | Publication date | Web location | Access date |
|---|---|---|---|---|
| U.S. Department of Agriculture, Forest Service | Copstead and others | 1998 | *http://www.stream.fs.fed.us/water-road/w-r-pdf/bibliography.pdf* | November 3, 2006 |
| The Natural Resources Defense Council | Ercelawn | 1999 | *http://www.nrdc.org/land/forests/roads/eotrinx.asp* | October 3, 2005 |
| Grand Canyon Trust | Brown and others | 2001 | *http://www.grandcanyontrust.org/lib/reports_studies.php* | October 3, 2005 |
| Washington State Department of Natural Resources | Coe | 2004 | *http://www.dnr.wa.gov/forestpractices/adaptivemanagement/cmer/finalreport1-4-05.pdf* | March 8, 2006 |
| WildlandsCPR | Anonymous | 2005 | *http://www.wildlandscpr.org* | November 7, 2006 |

Concern about the ecological effects of roads has been evident for at least four decades. The appearance of two books (Watkins, 1981; Forman and others, 2002) and a series of recent reviews (Bennett, 1991 [not seen]; Forman and Alexander, 1998; Spellerberg, 1998; Trombulak and Frissell, 2000; Jones and others, 2000; Gucinski and others, 2001; Brooks and Lair 2005) underscore the growing recognition of the importance of roads in both local and regional ecology. These reviews highlight the ability of roads to modify physical, chemical, and biological environments over scales ranging from a few meters to kilometers. They also highlight the functional roles of roads as conduits, barriers, or filters for the movement and dispersal of organisms at the landscape scale (including invasive plant propagules and microbial pathogens) and as habitat that can operate as either a source or sink in local population dynamics depending upon the species involved. The reviews also point out that, by providing access, roads can increase the use and alteration of habitats by humans. Spellerberg (1998) noted that road effects could be partitioned into those occurring during construction, the short-term effects of a new road, and long-term effects. Most of the research on the ecological and hydrological effects of roads has been conducted in mesic regions and often in areas of high relief. Although there are a large number of studies of the effects of ORV use on desert environments, very few studies examined hydrologic effects in areas of low relief.

## Literature Review

### 1. In what ways can roads affect an ecosystem's structure and functioning?

#### Road Effects That May Be Unrelated to Hydrology

Roads and their associated traffic can affect an ecosystem by affecting its structure, its functioning, or both (*see* **Glossary** for definitions). Roads directly affect ecosystem structure if they cause changes in an organism's behavior, physiology, fecundity, or risk of death. Obvious examples are disturbances to birds and mammals caused by traffic noise (reviewed in Kaseloo and Tyson, 2004), deaths and injuries to animals caused by collisions, and deaths and injuries to roadside plants and animals caused by pollutants originating from the road or its associated traffic.

Roads also directly affect ecosystem processes and thereby ecosystem functioning. For example, primary production is reduced by the extent to which the roadbed footprint eliminates vegetation. However, an off-setting increase in the productivity of roadside vegetation is often observed in deserts (reviewed in the next section). A more subtle effect on functioning is road dust settling on plant leaves where it causes a reduction in photosynthetic rates (Farmer, 1993). Road dust washed from plants or deposited directly on soil surfaces can affect soil chemistry (Grantz and others, 2003) and potentially could clog soil pores and reduce infiltration rates, thereby altering hydrological processes. An elevated roadbed (through-fill road; *see* **Glossary**) acts as a windbreak and can result in unnatural accumulations of snow or leaf litter on the leeward side of the road (fig. 2). All roads act as firebreaks.

Many researchers consider the most detrimental consequence of roads to be the reduction they cause in landscape connectivity (Andrews, 1990; Schonewald-Cox and Buechner, 1992), the structural attribute associated with the movement of organisms (including seeds and other propagules), materials (for example, surface water), or natural processes (for example, fire) across the landscape. As connectivity declines, so does the likelihood that abiotic processes and intra- and interspecific interactions in the landscape will continue to occur in their normal manner (Riley and others, 2006). Loss of connectivity stems from fragmentation of landscape elements (habitats) and the associated reduction in size and increased isolation of remaining habitat fragments. Isolated habitat fragments are subject to loss of species (and thus declining biodiversity). Species are lost when fragmentation disconnects an isolated population from

**Figure 2.** A depression, possibly a borrow-area for road fill, adjacent to an elevated (through-fill) road on the Baca National Wildlife Refuge. A culvert mouth is hidden in the area in shadow at the center-right portion of the image.

sources of colonists and the population dies out. Further, roads create edge habitat, and edges may provide points of entry for exotic invasive species (Pauchard and Alaback, 2004; 2006). Although invasion by exotics can be readily verified, documentation of native species loss due to habitat fragmentation requires long-term monitoring because of the potentially long lag times between fragmentation and local population extinction (Findlay and Bourdages, 2000).

In many instances, direct effects of roads are a result of (and quantitatively coupled to the level of) vehicular traffic rather than being directly caused by a road's presence. This appears to be the case, for example, in the spread of exotic plants. Seeds or other propagules are inadvertently transported by road construction and maintenance equipment and by vehicles using the road. Roads also can facilitate transport of pathogens and spread of disease in plant populations (for example, pathogenic fungus; Weste, 1977, cited in Spellerberg, 1998, p.321). Thus, the ability to manage traffic (road access) can be important in minimizing detrimental effects.

## Road Effects on Natural Hydrologic Patterns and Processes

Terrestrial hydrologic processes include precipitation, condensation, overland and stream flow, infiltration, evapotranspiration, subsurface percolation and flow, and the transport of solutes, nutrients, and particles by surface and subsurface flows. Roads can affect all of these processes, but direct effects on precipitation and condensation typically are minor and of little ecological importance in rural settings. Important ecological effects result from the capacity of roads to (1) modify local infiltration rates and thereby alter local surface-water and ground-water supplies, (2) obstruct surface flows in natural watercourses and thereby alter the pattern of surface and subsurface flows, (3) collect and store or reroute runoff, and (4) obstruct shallow ground-water flows and thereby alter the pattern of surface and subsurface flows. Roads also alter evapotranspiration rates, but its ecological significance may be secondary to other effects. Forman and Alexander (1998) reviewed road effects on hydrology using studies drawn largely from mesic areas featuring hilly or mountainous terrain. The authors report effects extending 50-100 m upslope and 200-1000 m downslope of the road, and sediment affecting streams more than 1 km downstream of the road. There is no mention of hydrological effects in low-relief landscapes nor does the review discuss the potential effect of fine particulates from unpaved roads (dust) on hydrology; for example, by clogging soil pores and thereby reducing infiltration capacity.

The part of the road where compaction has made the ground surface impervious will generate more runoff than would the area in the absence of the road. Some accounts suggest that all roads are essentially impervious, and thus the type of road will not matter as much as its width in determining the amount of runoff generated. Road design manuals stress that water should be kept off of, out of, and away from roads—at least while subject to traffic. Roads intended for use in all weather conditions are indeed made as impervious as possible and to readily drain, in order to minimize water uptake and retention. Some infiltration likely occurs, albeit at a reduced rate, on unimproved roads (defined in table 2) and graded dirt roads intended for use solely when dry or frozen; the presence of rooted plants on a road surface indicates that some infiltration is possible. Regardless of infiltration rate, the area occupied by roads is an important determinant of their hydrological effect because it directly determines the amount of runoff generated.

The runoff produced by a road surface may infiltrate into roadside soil and thereby alter the vegetation there. Johnson and others (1975) documented increased plant productivity along road margins in the Mojave Desert and attributed the increase to the extra water delivered to the margin by the road surface and, to a lesser extent, the road acting as a dam to collect runoff from upslope drainage systems. Standing crop biomass was enhanced along roads relative to off-road sites even when the bare road surface was included as part of the measured area. Similar findings were documented in semiarid New Mexico by Lightfoot and Whitford (1991).

Roads with a ditch on the upslope side will also affect the amount of water flowing in natural channels by intercepting runoff originating on the upslope side of the road and rerouting it to a pond or a road-drainage structure (for example, a culvert or rolling dip; *see* **Glossary**) through which it can pass to a pond or channel on the downslope side of the road. Greater road density, wider roads, and longer contributing ditch lengths (*see* **Glossary**) each contribute to higher discharge levels, which in turn can produce greater erosive force ("stream power") and more sediment (detached soil particles) being generated and transported. Coe's (2004) review cites Wemple and others (1996) and Croke and Mockler (2001) as providing evidence that roads often facilitate gully development below road-drainage structures such as ditch relief culverts, waterbars, or rolling dips. Jones and others (2000) produced a conceptual model of the effects of roads on hydrology in mesic, hilly terrain (Oregon's Cascade Mountains). They argued that roads are hydrologically connected to the stream network and affect the manner in which incoming precipitation is routed through a basin to produce a flood. They suggested that roads can increase the frequency and intensity of flood peaks in natural channels and that roads also affect the frequency and extent of debris flows. The latter, which typically originate as landslides on steep slopes, are considered to be a more significant form of disturbance in stream corridors than are high flows (floods) by themselves. Phippen and Wohl (2003) examined a series of subbasins within the Rio Puerco watershed of northwest New Mexico and found that basin sediment load was highly sensitive to the presence of unpaved roads, which they suggested served as high gradient, channelized conduits of water and sediment during storms. Studies of the downstream effects of dams have shown that changes in the magnitude, duration, timing, frequency, and rate of change of flows can each adversely affect streamside organisms.

A major mechanism causing road-induced alteration of hydrologic patterns in hilly terrain is the interception of subsurface flow at road cuts, which leads to the transformation of slow subsurface flow to rapid surface flow. Because road cuts are uncommon or absent on the relatively flat Baca NWR, this mechanism probably is unimportant. However, an analogous mechanism involving interception of surface runoff would occur if roadside ditches are constructed to intercept and capture surface flows to protect road surfaces from erosion during sheet-flow producing storms. Schlesinger and Jones (1984) and Schlesinger and others (1989) studied the effects of ditches (and dikes on the downslope side of the ditch formed from the excavated soil) on vegetation growing on slopes subject to sheet flow during intense rainstorms in the Mojave Desert. They found reduced shrub density and biomass below the ditches, where surface flow would have been greatly reduced or eliminated, and associated it with reduced percolation of water into the soil.

The different kinds or greater biomass of vegetation produced in roadside areas where soil moisture is augmented by road runoff potentially could serve as a sink or filter for both surface and subsurface flows, but no study was found that addressed this issue. Greater total leaf area likely would translate to greater transpiration losses, whereas greater stem density in roadside ditches could slow runoff and promote sediment deposition. Road density again would be a major factor in determining the overall importance of these effects.

No study was found that causally linked road effects on hydrology to changes in aquatic ecosystems in a semiarid or arid area. However, Gray and Smith (2005) associated a shift from natural grassland to agriculture, which would presumably entail development of a road network, with reduction in body size of amphibians resident in nearby playa lakes. They attributed the size reduction to a shift in hydroperiod brought about by the change in land use, but no specific role for roads was presented.

## 2. Are there particular problems or concerns associated with unpaved roads?

Brooks and Lair (2005) reviewed effects from a range of "vehicular routes," including three types of unpaved roads (table 2). A "gravel road" always implies gravel has been added to the surface, and the authors note that the source of gravel often is different from the local parent soil material. This imported material can modify local soil and ground-water chemistry. Although their classification scheme may not satisfactorily differentiate all unpaved roads (for example, in cases where berms are consistently absent on an improved local road), it serves as an example of how roads might be classified on the Baca NWR.

Brooks and Lair (2005) provide a figure showing berms on both sides of unpaved roads, which may be a common, but not necessarily intentional, result of grading in relatively flat areas.

**Table 2.** Characteristics of three types of unpaved roads (after Brooks and Lair 2005). [ORV, off-road vehicle; m, meters]

| Type | Width | Characteristics |
|---|---|---|
| Undeveloped (unimproved) local road | One lane | Without any grading or scraping of surface, with no shoulder and no or low berms. These roads grade imperceptibly into two-track or ORV routes. |
| Improved local road | One or two-lane | Improved by grading or scraping (thus, typically lacking topsoil), and perhaps by having gravel added to stabilize the surface, usually with little or no shoulder and medium berms. |
| Collector road | Two-lane dirt or gravel | 7-10 m wide and feature narrow shoulders and high berms. |

Berms are added intentionally to contain road runoff and (or) to stockpile material for subsequent maintenance activities. Many figures accompanying construction manuals for unimproved roads show only a single berm on the outside (downslope) shoulder or no berms at all. Presumably, berms are intentionally constructed on the upslope side of the road to intercept overland flow (if no inside ditch is present) and to collect runoff on a crowned or insloped road (*see* **Glossary**). The roadbed and berms of unpaved roads may serve as a source of sediment that can be transported by overland runoff during storms or snowmelt. Thus, road width and the presence and size of berms can be significant determinants of hydrological effects. Vehicular traffic and some maintenance activities (for example, grading) tend to generate finer and more erodible material (Ziegler and others, 2004).

The material making up the roadbed also has a role in determining the overall effect of the road. Ziegler and others (2001) pointed out that the erodability of the road surface materials depends primarily on their physical and chemical properties, including texture, clay mineralogy, oxide composition, organic matter content, exchangeable sodium content, shear strength, and bulk density. Raindrops striking the road surface and water flowing over it detach particles from the consolidated roadbed surface and transport (via splash and flow) both those and previously detached particles. However, the erosive capability of rain (its ability to detach and move particles by splash) is a function of raindrop size and velocity (Salles and Poesen, 2000) and typically increases with storm intensity.

Surface runoff generated by impermeable road materials may flow preferentially down a road rather than cross it. Elliot and others (1999) found that insloping and outsloping effects on low-traffic-volume roads often are overshadowed by the effects of rutting. They suggested that most soil erosion on roads is from concentrated flow in ruts or ditches and noted that adding gravel increases hydraulic conductivity and reduces erosion. A layer of protective gravel on the road surface also would effectively reduce rain erosive capability by preventing raindrops from directly hitting the finer textured and more easily detached and transported roadbed material (fig. 3). Erosion from an unpaved road surface is affected by road steepness, the overland flow distance, and the amount and kind of vehicular traffic (Ziegler and others, 2004).

Unpaved roads do not have the issue of runoff contaminated with chemicals associated with paving materials (for example, asphalt) and they tend to be narrower than paved roads. However, runoff from unpaved roads may become contaminated from chemicals used to reduce dust or stabilize the road surface (for example, hexahydrated magnesium chloride; Thenoux and Vera, 2003). Some types of pollution are strongly related to the amount of traffic (for example,

**Figure 3.** A gravel-surfaced through-fill section of the Lexam Road on the Baca National Wildlife Refuge. Note the shallow roadside ditch possibly added to protect the toe of the fill.

heavy metal pollution that originates from vehicle exhaust and the wearing of vehicle parts) and, thus, are less likely to be associated with unpaved roads than highways.

Dust typically is produced during vehicular passage down an unpaved road. Santelmann and Gorham (1988) and Kalisz and Powell (2003) document adverse effects of road dust on roadside plants and animals. The latter study also showed a marked increase in soil pH near the road because of calcareous dust additions to a naturally acid soil. Dust effects are discussed further in the next section.

## 3. Are there special concerns associated with unpaved roads in semiarid and arid landscapes?

Unpaved roads in semiarid and arid landscapes can affect hydrology and are susceptible to erosion just as are unpaved roads elsewhere. Where precipitation occurs primarily in the form of intense rainstorms, as is often the case in the semiarid and arid western United States, surface runoff from roads can be expected to be relatively high, even when little runoff is generated from adjacent land. The amount of erosion per precipitation event also may be relatively high because of the condition of the road surface. Ziegler and others (2001, p. 236) noted that the erodability of an unpaved road is controlled by both the erodability of the underlying compacted road surface and that of the loose surface material. The supply of loose surface material is constantly altered by surface runoff that moves it downslope, by traffic that redistributes it on the road surface and generates the crushing/mixing forces that alter its aggregate size distribution, and by detachment processes that generate more of it from the consolidated road surface or roadside margin. Thus, erodability of the surface material depends upon numerous factors, changes over time, and can be quite high where a long dry period has led to traffic creating a thick layer of loose material (Ziegler and others, 2001). Effects from off-road vehicles (ORVs) in arid landscapes were studied by Iverson and others (1981), who found that "roughly a century is required for bulk density, strength, and infiltration capacity to be restored" following disturbance. Iverson and others (1981) noted that ORV effects include reductions in both the effectiveness of soil-surface stabilizers and in resistance to overland flow. A major difference between effects of unpaved roads in semiarid and arid areas and those in areas with higher precipitation is the amount of dust that is generated and subsequently settles on roadside plants and soil surfaces. Dust deposits are removed at least partially by rain, but frequency and magnitude of rainfall may be important. Dust coatings can reduce plant productivity and may affect animal activity and survivorship. The coatings also can harm biological soil crusts. These crusts, a community of cyanobacteria, lichens, and mosses that live on the soil surface (but show metabolic activity only when wet; Belnap and others, 2004), occur in semiarid and arid areas throughout the world. They are a critical ecosystem component contributing to soil fertility and stability, in part through their ability to promote infiltration and thereby reduce runoff and associated erosion (Barger and others, 2006). Disturbance to soil crusts from road construction or dust deposition, therefore, would potentially increase runoff and soil erosion.

Semiarid and arid roadside areas also are susceptible to vegetation change as a result of factors associated with vehicular traffic, including nitrogen additions and propagule dispersal. Brooks and Lair (2005) provide a good review of studies documenting that roads are a primary pathway for exotic plant invasions into semiarid and arid ecosystems. They cite papers by Johnson and others (1975), Amor and Stevens (1976), Brooks and Pyke (2001), and Gelbard and Belnap (2003), and note that vehicles primarily serve as dispersal vectors. More recently, Pauchard and Alaback (2006) found road edges much more likely than other edge types (burned forest and clearcut) to harbor exotic species in semiarid Wyoming. They argue that propagule dispersal is a key constraint to exotic species invasion, and that establishment along edges requires a propagule source sufficiently close to generate a frequent and abundant seed rain or alternatively, an efficient dispersal vector (for example, traffic or machinery).

Native species grow slowly in the harsh environment created by the normally low soil-moisture level in semiarid and arid regions. The generally slow growth of early successional native plant species (as well as early successional forms of biological soil crusts) means that berms and road edges are slow to develop a protective cover of native vegetation that can help to reduce erosion. Once exotic species adapted to such environments gain a foothold, the subsequent high productivity promoted by the relatively high roadside soil-moisture levels can facilitate their spread via runoff or by traffic. Differences in soil depth, texture, and chemistry also may contribute to higher rates of establishment of exotics in roadside environments than in more distant (interior) locations.

### 4. In what ways can roads affect hydrology on the Baca National Wildlife Refuge?

There are no paved roads on the Baca NWR. The unpaved refuge roads were developed (1) as part of the traditional haying and grazing operations, (2) to facilitate recent gas and oil exploration and production operations (the Lexam Road), and (3) as part of the Bureau of Reclamation's Closed Basin Project (CBP, U.S. Department of the Interior). The Lexam Road (fig. 1) crosses wet-meadow habitat in the northeastern portion of the refuge, whereas much of the CBP road network occupies habitat close to playa wetlands in the western portion of the refuge. The least-improved roads are those used to provide access for managing the wet meadow irrigation system, to facilitate harvesting and hauling the wild hay, and to manage livestock. It is unclear whether these ranch roads can all be classified as undeveloped (*see* table 2). The CBP roads access ground-water pumps, conveyance pipes, and monitoring wells, as well as overhead electrical transmission lines. The CBP roads are characterized by having a gravel (all-weather) surface elevated above local ground level, and many are placed directly over water-conveyance pipes. The Lexam Road also is improved to allow all-weather use. Both the CBP roads and Lexam Road likely would fall into the category of improved local road (table 2) although berms are often absent. None of the refuge roads are currently open to the general public.

As previously noted, roads can affect numerous hydrologic processes including infiltration of surface water into the soil and the quantity, quality, and routing of surface-water and ground-water flows. A conceptual model of the manner in which roads can affect surface-water hydrology at a point downslope of a road is presented in figure 4.

Infiltration is reduced on all road surfaces. Infiltration also may be reduced along the road margin if fine sediment deposited in ponded runoff seals the soil surface or if road dust clogs soil pores. Both elevated roadbeds and the berms along the margins of an unraised graded (scraped) road interrupt flows where the roads cross a natural drainage channel unless a road-drainage structure is present to allow unimpeded flow (fig. 4). Historically, the design of culvert installations (culvert size and position) typically was intended to eliminate the risk of roadbed damage during runoff (discussed below) and not necessarily to prevent or even minimize alteration of natural hydrologic patterns. A roadbed constructed entirely of fill material placed over poorly permeable soil can result in the nearly complete interception of flowing groundwater (Hartsog and others, 1997), leading to alteration of groundwater flow paths and (or) a rise in the water table (fig. 4). Surface flows in minor channels intersected by the road may be ponded intentionally by the roadbed if the water volume involved is considered nonthreatening to roadbed integrity.

Water ponded on the upslope side of a roadbed (fig. 5) can infiltrate into the soil and contribute to shallow ground water or be lost through evaporation (fig. 4). If evaporation predominates, soil salinity or other chemical attributes may be altered. More likely, water in minor channels intercepted by the road is diverted into a roadside ditch and carried downslope to a larger natural channel where a culvert passes the collected water to the downslope side of the road. The number (frequency along the roadway), size, and position (particularly bottom elevation, slope, and orientation relative to road axis) of culverts thus affect both the route and rate of surface-water passage from the upslope to downslope sides of the road.

The potential for a road to affect hydrology was recognized by early pioneers. Some of the roads on the Baca NWR originally constructed to manage irrigation or hay harvesting may have been intentionally designed to serve as “dams.” The elevated roadbed or the roadside ditch can effectively gather surface sheet flows and shallow ground water produced by upslope diversions and convey the water to a road-drainage structure. Once below the road, the water can be respread at desired points in meadows below the road.

Sheet flow or Horton overland flow (HOF) occurs whenever rainfall intensity, the pace of snowmelt, or the application rate of irrigation water exceeds the rate at which water can enter the soil, defined by the soil’s infiltration capacity, and drain or percolate downward, defined by the soil’s saturated hydraulic conductivity. In any soil, the infiltration capacity declines as the topsoil becomes saturated, potentially decreasing to equal the soil’s saturated hydraulic

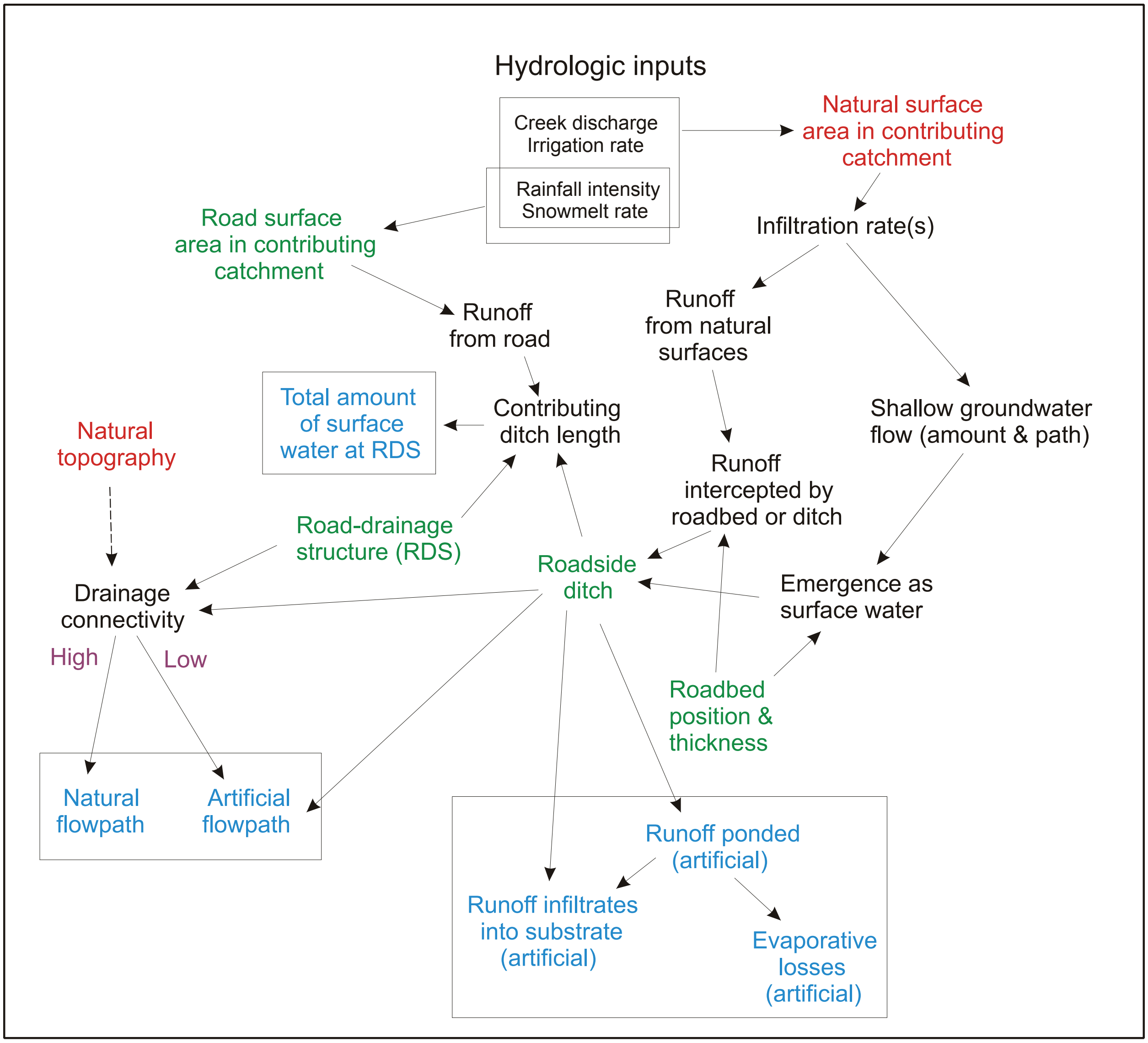


**Figure 4.** Conceptual model of linkages between road attributes (green lettering) and surface water hydrology (blue lettering) evaluated at the outlet of a road-drainage structure (RDS). Arrows show the direction of affect.

conductivity (Dunne, 1983). The initial or maximum infiltration capacity of soils in semiarid and arid regions is determined by a suite of attributes, including soil texture (a sandy loam has a higher infiltration capacity than a silt loam or clay loam soil), organic matter content (higher levels promote infiltration), the density of macropores (created by soil fauna and plant roots; higher density promotes infiltration), and the presence or absence of a macrobiotic surface crust (the crusts promote infiltration; Belnap and others, 2005). The abundance of macropores (radius greater than 0.05 mm) also largely determines saturated hydraulic conductivity because these pores account for most movement of water through a saturated soil (Brady and Weil, 2002, p. 197). The infiltration capacity of undisturbed surface soils on the Baca NWR, which range from sands to clays, is widely variable.

**Figure 5.** Lexam Road near Willow Creek with wet meadow irrigation water ponded on the upslope (east) side. June 2004 photo courtesy of M. Stuebe.

Roadbed and road surface materials other than gravel have a very low infiltration capacity because they are highly compacted and have little or no pore space, either by design or as a result of vehicular traffic. Thus, roads not only operate as hydrologic dams by intercepting sheet flow generated on upslope landscapes, they also can be a source of runoff during snowmelt or low-intensity rainstorms that produce no sheet flow in the surrounding landscape. The slope of the road surface, which determines whether the sheet flow it generates drains to the upslope (into an inside ditch) or downslope side of the road, also will have an effect because runoff concentrated in an inside ditch must either pond there, infiltrate into the soil, or be carried as a concentrated flow via culvert or other road-drainage structure to the downstream side of the road. Thus, the total length and surface area of roads, their orientation with respect to natural drainage paths, whether a road section is insloped or outsloped, the nature of roadside ditches, the nature of road berms, and the distribution of road-drainage structures are key variables in determining how roads affect an area's hydrologic response to rainfall and snowmelt. These hydrologic effects are measurable at scales of 10 to 100's of meters and from the upslope to downslope side of a short section of road. For example, Lightfoot and Whitford (1991) argued that road runoff, along with reduced evaporation from soil under the road, was responsible for a higher shrub density, greater individual shrub vigor, and higher density of foliage arthropods along a paved desert road margin than at positions 20 m farther away. Unfortunately, they did not measure soil-moisture levels.

As noted earlier, Schlesinger and Jones (1984) and Schlesinger and others (1989) examined effects of artificially reduced overland flow on plants occupying a shallow (2-degree) slope in the Mojave Desert. Ditches intercepted overland flow (generated in mountain uplands) and conveyed the runoff around the downslope "experimental" areas, in a manner analogous to a roadside ditch diverting runoff. Both shrub density and biomass were less below compared to above the ditches after approximately 50 years of runoff diversion. Soil characteristics suggested reduced percolation in the experimental areas as would be expected if only incident precipitation contributed to soil moisture there. No detectable effect of the diversion on surface soil erosion was found, suggesting that sheet flow does not cause erosion on undisturbed ground surfaces.

Even if culverts allow unimpeded surface flows at major drainage channels, elevated and insloped roads can alter hydrologic functioning at the landscape scale by damming smaller natural channels and capturing flows from the upslope portion, thereby drying the downslope portion of the channel. The captured water may be transported in the ditch to a culvert where it creates a new route (channel) or augments flows in an existing one. By affecting the quantity of runoff flowing in a channel and altering the distribution of water on the landscape, hydrologic and ecological functioning is altered.

The gentle slopes prevalent on the Baca NWR (fig. 6) mean less effect from gravity on erosional processes; overland flow is slower, initiation of downslope movement of detached soil particles is more difficult, and movement, once initiated by gravity, wind or water, tends to be for shorter distances. Thus, hydrological effects that promote erosion may be less detrimental on the Baca NWR than at locations with steeper slopes. The potential effects from road-related erosion should not be discounted, however. The lengthy sections of elevated road may (at least during low- or moderate-intensity runoff) serve as dikes, retarding flows, ponding water and allowing the upslope side of the roadbed to act as a sediment trap. It is also possible that the road fill is itself a source of sediment or that roads route water in a manner that increases erosion in natural channels and sediment deposition in the terminal playas. Larger sediment loads transported to terminal playas will raise the water-level surface (analogous to adding marbles to a glass filled with water) and result in the inundation of new areas at the playa margin. Increased sediment loads will also increase the water-surface area, which will lead to greater evaporative water loss. The increased water loss could in turn alter hydroperiods in historically inundated sites and soil chemistry elsewhere, leading to changes in plant communities. In the case of playas in the San Luis Basin, however, change in water surface elevation due to sediment deposition may be confounded by change due to land subsidence associated with ground water withdrawals.

## 5. Are effects on hydrology localized near roads or can they be widely distributed in the landscape?

The effects of roads on hydrology will be clearly felt on a local scale because of changes in roadside hydrology, channelization of flow via culverts, and similar factors. However, effects may be felt at a much larger spatial scale through (1) cumulative impacts, which would relate to road density, and (2) the ability of hydrologic effects to be transmitted long distances via altered quantity or quality of flows in new or existing channels. For example, roads in the eastern portion of the refuge could be affecting the conditions in the playas on its western margin.

Nonhydrological, dispersed landscape effects of roads and other vehicular routes (for example, tracks in fields) can be difficult to measure. Brooks and Lair (2005) noted that even when route densities of various types can be correlated to environmental variables, the primary cause-and-effect relationship can be difficult to identify.

**Figure 6.** A dry watercourse crossing on a through-fill section of the Lexam Road in Baca National Wildlife Refuge. View is to the west, looking "downstream."

### 6. Can rare hydrologic events (intense storms, droughts, and so forth) lead to new or magnified road effects?

No study was found that specifically addressed road effects resulting from rare hydrologic events. It is reasonable to expect dramatic change in the kinds or magnitudes of effects, however, because hydrologic patterns and processes often are threshold-dependent. For example, a watercourse may carry surface water only during very intense rainstorms, or very heavy runoff might be necessary to produce the water volume and velocity required to initiate erosion along a roadside ditch.

Antecedent conditions, including factors unrelated to hydrology, can affect the nature of effects from rare hydrologic events. For example, in a retrospective case study conducted in mountainous terrain, Watterson and Jones (2006) argued that unprecedented interactions between a road and a stream network during a record rainstorm allowed two exotic plant species normally restricted to the road margin to invade the stream margin. These authors speculated that usually high overland flows can entrain seeds and carry them to roadside ditches in a variety of landscape settings, from which they can be transported in the collected runoff to otherwise inaccessible locations in natural stream channels. Another example is provided by intense rainstorms with large, fast-moving raindrops that strike road surfaces already loose due to saturation, leading to unusually high sediment production through both impact-induced erosion (Kinnell, 2005) and gullying below culverts triggered by high runoff. In contrast, a drought of sufficient intensity could cause plant deaths in areas where soil moisture, abnormally low because of road effects, drops below a critical threshold. By its very nature, investigation of the effects of rare hydrologic events will usually require long-term monitoring.

## 7. How can road effects on natural hydrology be minimized?

Environmentally sensitive road design includes the goal of minimizing alteration of natural hydrologic processes. For example, design criteria for Bureau of Land Management (U.S. Department of the Interior) "temporary" or Forest Service (U.S. Department of Agriculture) "short-term" roads include the following (taken from material in the Roads and Access Ways section of "Surface Operating Standards for Oil and Gas Exploration and Development Gold Book," available on the Web at *http://www.blm.gov/utah/vernal/minerals/goldbook.html*, accessed April 3, 2006):

- Ensure drainage control over the entire road through the use of drainage dips, insloping, natural rolling topography, ditch turnouts, or culverts. Culverts, drainage crossings, and other controls should be designed *for a 10-year frequency or greater storm* (author emphasis), with an allowable head of 30 cm (1 ft) at the pipe inlet.
- Roadbed culverts should be used to drain inside road ditches when drainage dips are not feasible.
- Install ditch relief culverts to periodically relieve the ditch line flow by piping water to the opposite side of the road where the flow can be dispersed away from the roadway. The spacing of ditch relief culverts is dependent on the road gradient, soil types, and runoff characteristics.
- A culvert with a 46-cm (18-in.) diameter is the minimum for ditch relief to prevent failure from debris blockage.
- The depth of culvert burial must be sufficient to ensure protection of the culvert barrel for the design life of the culvert. This requires anticipating the amount of material that may be lost due to road use and erosion.
- Ditch relief culverts can provide better flow when skewed 15 to 30 degrees downgrade from a line perpendicular to the centerline of the road. This improves the flow hydraulics and reduces siltation and debris plugging the culvert inlet. Culverts placed in natural drainages can also be utilized for ditch relief.

Similarly, core principles of environmentally sensitive road maintenance include avoiding the discharge of sediment or other pollutants into creeks and other wetlands, maintaining natural drainage patterns, and providing for fish passage (Fishery Network of the Central California Coastal Counties, 2004). Maintaining natural drainage patterns in larger channels is relatively straightforward, but it may be difficult to maintain flow continuity from one side of a road to the other where the road crosses small channels draining slopes as shallow as those found on the Baca NWR. Where roads intercept sheet flow runoff from the upland, passing the water to the downstream side of the road without altering it quantitatively or qualitatively becomes impossible. Because roadbeds and road surfaces tend to be major sources of sediment, ideally upland runoff and road-surface runoff should be routed separately, with upland runoff going into natural drainage channels and sediment-laden road runoff channeled into local sediment sinks. In practice, however, the two can seldom be separated, and sediment retention takes precedent over maintaining hydrologic connections. For example, a guideline for county road maintenance intended to protect aquatic habitat in coastal California is to "[d]isconnect and disperse flow paths, including roadside ditches, which might otherwise deliver fine sediment to stream channels" (Fishery Network of the Central California Coastal Counties, 2004, p. 5-6). In this view, complete hydrologic connectivity between surface water collected in roadside ditches and natural channels is undesirable. These guidelines further advocate elimination of ditches and ditch relief culverts wherever possible on unpaved roads, substituting outsloping with rolling dips to facilitate water movement across the road surface.

Unpaved roads intended for industrial use have the potential to produce more sediment than the same road used by lighter, non-industrial vehicles. The Conservation Management Institute and Virginia Polytechnic Institute and State University have produced a "best practices" guide for low-volume roads titled "Low-Volume Roads Engineering—Best Management Practices Guide," written by Forest Service engineers and funded by the U.S. Agency for International Development. Low-volume roads, which by definition have little traffic, often are built to access or extract resources and must accommodate heavy trucks that potentially can produce extreme axle loads. The guide is intended to educate interested parties about practices that can be used to avoid or minimize the adverse environmental impacts of road building and maintenance. The publication is available at the International Road Federation Web site (*http://zietlow.com/manual/gk1/web.doc*, accessed September 27, 2005).

In the case of the Baca NWR, the extent to which CBP roads, the Lexam Road, and other roads were designed with potential hydrological and ecological impacts in mind is unclear. The current road network appears to be a result of joining roads constructed at various times and for various purposes, with construction and maintenance efficiency and travel convenience as foremost considerations. An important question is whether existing roads and the road network can efficiently handle runoff, minimize sediment production, and minimize sediment delivery to major channels during rare, large-magnitude events (for example, one in 25-year or one in 50-year precipitation or snowmelt events). If significant sediment production is unavoidable, it may become necessary to choose between altering natural hydrologic processes in order to trap sediment near the source roads or allowing sediment to enter stream channels and alter hydrologic processes there and in the terminal playas. Reducing contributing-ditch lengths by increasing the frequency of road-drainage structures may be the best means to assure near-normal flows downslope of a roadbed that is elevated above the level of the surrounding ground surface. Natural hydrologic patterns also can be maintained by preventing travel on wet (soft) roadbeds when disturbance to road-drainage structures and generation of sediment is most likely to occur. Lovich and Bainbridge (1999), noting the sensitivity of vegetation and soils in desert habitats to disturbance and the very long time required for natural recovery, suggest the best management option is to limit as much as possible the extent and intensity of impacts.

## 8. What are the costs and benefits of road removal?

Switalski and others (2004) define road removal as "the physical treatment of a roadbed to restore the form and integrity of associated hill slopes, channels, and flood plains and their related hydrologic, geomorphic, and ecological properties and processes." They reviewed three methods of road removal, noting that each produces "short-term" disturbance that can increase sediment loss. They also noted there is currently insufficient data to compare how effectively each method restores ecosystem processes and an almost complete lack of studies on the extent to which road removal restores ecosystem structure. None of the studies cited by these authors dealt with desert roads. Vegetation-management techniques could be used to accelerate desired vegetative recovery on roadsites. For example, Parmenter and others (1985) describe planting containerized individuals of several shrub species in pre-arranged spatial patterns to accelerate successional processes on reclaimed surface-mined lands in semiarid western Wyoming.

Road closure with no subsequent physical treatment is an alternative to road removal, but the time required for full restoration of ecosystem structure and functioning can be very long. Bolling and Walker (2000) examined soil and vegetation dynamics along dirt roads that had been abandoned for periods ranging from 5 to 88 years in southern Nevada. Roads were of two kinds—"bladed" roads that had been created by bulldozer scraping (thus featuring lateral berms and lacking topsoil) and "track" roads created only by recurring surface vehicular traffic (characterized by a raised center berm). Roads topped with gravel were specifically avoided. These workers found that none of 11 soil parameters measured varied with road age (time since abandonment) and suggested that successional changes in soil attributes were operating on the scale of centuries or millennia. Track roads were more compacted than bladed roads or control sites, and soils of track roads had higher clay and organic matter content but lower nutrient levels (nitrogen and phosphorus). Vegetative cover did not change over time, but plant composition did, and the pattern on bladed and track roads differed. The authors argued that soil factors played only a minor role in initiating and controlling the rate and direction of succession on the roads; they suggested recruitment resulted from chance events, sprouting by residuals that survived road creation and use, or climatic or other factors not examined in the study.

## Conclusions

Roads affect most terrestrial hydrologic processes. Although no study of road effects on hydrology has been undertaken in a semiarid, low-relief landscape featuring creeks and other wetlands comparable to the Baca National Wildlife Refuge, the large amount of work in other ecosystems provides a clear picture of potential road effects on the refuge. Roads directly affect surface-water and ground-water hydrology by impounding runoff and by altering infiltration, surface and shallow subsurface flow paths, water table dynamics, and evapotranspiration. Roads also indirectly affect hydrology through their effects on sediment generation and transport, and on roadside vegetation and associated evapotranspiration. Effects may be primarily small and local, but large and distant effects are possible as a consequence of potential effects on streams, potential effects from unusually intense storms or other rare hydrologic events, and cumulative effects linked to road density. Road effects on hydrology are likely to be ecologically important in environments like that of the Baca NWR, where relatively small changes in the amount of water can exert a large influence on upland, streamside, and wetland biota. Documentation of road effects on hydrology requires measurement of both qualitative and quantitative aspects of hydrology at locations where effects are likely to be pronounced—above and below roads that cross slopes, along roadside ditches, at road-drainage structures, and in affected depositional areas. Undesirable changes to natural hydrologic patterns can be minimized by thoughtful attention to hydrologic concerns in road design, construction, and maintenance. A number of manuals presenting guidelines for environmentally sensitive road design are available and appear applicable to the Baca NWR. Restoration of hydrologic patterns and processes is a necessary, but not a sufficient condition for restoration of an ecosystem's natural structure and functioning. The effectiveness of road removal to restore desirable hydrologic conditions in a landscape adversely affected by roads has not been studied in sufficient detail to warrant a clear endorsement.

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## Glossary

### Berm
A curb or dike constructed to control water and prevent road surface runoff from discharging onto roadside slopes and (or) to provide material for subsequent road maintenance.

### Contributing ditch length
The length of roadside ditch contributing runoff to a road culvert, rolling dip, or other water conveyance feature, measured in meters or kilometers.

### Crowned road
A road with a surface constructed so that runoff drains approximately equally to both sides.

### Ditch relief culvert
A culvert placed to allow water collected in an inside ditch on the upslope side of the road to flow in a controlled manner under the road surface to the downslope side. A type of road drainage structure. Choosing where to use a culvert versus a rolling dip or water bar to control runoff and road erosion involves an understanding of the advantages and disadvantages of each.

### Drainage connectivity
The extent to which the drainage features associated with the road system (for example, roadside ditches and culverts) are directly linked to the natural channel network, expressed as proportion of the total road length connected to the channel network. The proportion not connected must either generate insufficient runoff to cause water to flow or any new channels formed by the generated flow lead to new detention areas (e.g., ponds). The term "connectivity" has a different meaning in landscape ecology applications (see p. 4).

### Drainage density
The density of drainage channels in a specified area, measured in meters per square meter or kilometers per square kilometer.

### Ecosystem
A suite of interacting organisms and their environments in a defined area, characterized by the presence of linked (functionally integrated) biological, physical, and chemical processes that lead to clearly defined trophic structure and material cycles.

### Ecosystem functioning
The kinds and rates of processes that are taking place in an ecosystem. Ecosystem processes include production of biomass (for example, primary and secondary production), nutrient sequestration and cycling, and water infiltration and storage. *See* **Ecosystem structure**.

### Ecosystem structure
The kinds, numbers, and dispersion patterns of organisms present in an ecosystem at a point in time. The relationship between ecosystem structure and functioning is not completely understood, leading to controversy over the roles and importance of particular species and genotypes in a given ecosystem. Biodiversity and ecosystem functioning relationships are reviewed in Chapin and others (2000) and Loreau and others (2001).

### Fill
The material that is placed in low areas, compacted, and built up to form the roadbed surface.

### Fillslope
That part of a road fill between the outer edge of the road and the base of the fill, where it meets the natural ground surface.

### Hydroperiod
The seasonal pattern of the water level in a wetland.

**Inside ditch**
Ditch constructed on the upslope side of a road to collect and hold or direct runoff originating from upslope and possibly also the road surface. The road surface would typically be either crowned or sloping slightly (2-4 percent) outwards (downhill). An inside ditch would typically be coupled with a type of road drainage structure if the road is traversing a sloping surface.
**Insloped road**
A road with a surface that slopes downward toward the cutbank. An insloped road section is typically constructed with an inside ditch that collects runoff from the road surface and the cutbank.
**Landscape/landscape ecology**
A landscape is an area made up of multiple habitats or ecosystems (landscape elements). Landscape ecology is the study of how the kinds and configuration of the different elements (landscape pattern or structure) affect processes such as flows of water, soil, chemicals, or energy; movements of organisms, including humans; and movement of products, resources or capital.
**Outboard berm**
A mounded earthen curb along the outboard edge of a road, usually generated by the periodic grading of the road. Berms trap water on the road.
**Outsloped road**
A road with a surface that slopes away from the cutbank toward the road's fillslope. Outsloped roads typically do not have an inside (inboard) ditch. If present, the inside ditch collects runoff solely from the cutbank, whereas road runoff drains toward the fillslope.
**Outsloping**
The process of converting an insloped or crowned road to an outsloped road.
**Quickflow**
The pulse of (additional) surface water flowing in a channel as a result of a storm.
**Road density**
The density of roads of a given type in a specific area, measured in kilometers per square kilometer.
**Road drainage structure**
Any of various structures (for example, culvert, rolling dip, water bar) to drain surface water away from a road.
**Road grade**
The slope of a road along its alignment, that is, in the direction of travel.
**Roadside verge(s)**
The edge, brink, or margin of a road, or a grassy border, as along a road (British).
**Rolling bar**
—*see* Water bar.
**Rolling dip**
A stabilized dip or depression in a road-surface elevation (relative to ground-surface elevation) to allow water collected in an inside ditch on the upslope side of the road to flow in a controlled manner across the road surface to the downslope side. A type of road drainage structure. Also termed "swale," "stone ford," "broad-based rolling dip," or "waterbreak." A rolling dip can be used in place of a culvert to handle moderate seasonal flows, especially where or when there is minimal traffic, to drain stormwater, or to act as an emergency spillway over a road in conjunction with a culvert that may not be large enough to handle large flows. Choosing where

to use a culvert versus a rolling dip or water bar involves an understanding of the advantages and disadvantages of each.

**Stream power**

The rate at which a stream can do work, especially the transport of its load. Stream power is largely a function of discharge and channel slope and is expressed as the product of the specific weight of water, discharge, and slope. Thus an increase in runoff flowing down a roadside ditch or natural channel will increase the erosive power of the water as well as the sediment load the water can carry.

**Subdrainage (subsurface drainage)**

The flow of water beneath the surface of the ground (shallow ground-water). Along roads, specific construction techniques can be used to ensure that subsurface drainage is not impeded by the road bed or road fill.

**Through-fill road**

An elevated roadway with fill slopes below both sides of the road, that is, a roadbed entirely constructed of fill. A through-fill road with a non-zero road grade is often constructed with a berm along both sides in order to retain road surface runoff on the road and direct it to a single discharge point, usually a fabricated metal berm-drain. Through-fill roads with both sides bermed are typically found at sensitive stream crossings. Through-fill roads are also used to cross wet or swampy ground or especially flat terrain where water is likely to sit. Some manuals advocate protecting the toes of the fill slopes from erosion by constructing parallel runoff interceptor ditches.

**Water bar (Waterbar)**

A shoulder or berm (obstruction), possibly accompanied by a shallow ditch, placed at an angle on the road surface and tied to the upslope hillside to divert water flowing along the road and inside ditch to the downslope side of the road. Also termed “rolling bar.” A type of road drainage structure. Waterbars are closely related to rolling dips but are a much more abrupt rather than gradual. They are often used on steep grades where traffic is minimal and travels slowly, and the road is not plowed during the winter. Temporary waterbars are often constructed on logging or construction roads by placing a log across the road; more permanent waterbars can be constructed of pressure-treated lumber. Variations of the water bar include the open top box culvert that leaves the surface of the road flat except for a narrow channel, and rubber strips that stick slightly above the road surface to intercept water but let vehicle wheels easily pass. The disadvantage of waterbars is that they are difficult to maintain through the winter, so are generally limited to seasonal road use.

**Watercourse**

A natural or artificial channel through which water flows.

**Water turnouts and spreaders**

Water turnouts are channels constructed to convey water collected in an inside ditch away from the road and onto adjacent ground where it can infiltrate into the ground. The channels allow the erosive energy of the water to be dispersed while also trapping suspended sediments in the soil as the runoff soaks into the ground. “Spreaders” are widenings at the end of a water turnout that spread the water over as large an area as possible to further reduce velocity and maximize infiltration area.