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Impacts of Floods and Avalanches

ABSTRACT

Floods in the Sierra Nevada are produced by snowmelt, winter rainfall and rain-on-snow events, summer thunderstorms, and failure of impoundments. Floods routinely modify channel conditions and therefore affect aquatic and riparian communities. Riparian vegetation has a variety of interactions with peak flows and sediment transport. Floods function as a disturbance mechanism primarily as they damage or remove riparian plants and alter riparian habitat. Land management or disturbance alters flood processes mainly if changes in land cover are dramatic and extend over a large fraction of a river basin.

Avalanches are a natural process that occasionally alters forests at higher elevations. The location of a forest stand with respect to avalanche-prone terrain is the primary risk factor. Stands in vulnerable locations are subject to destruction on an irregular basis. Weather and snow conditions determine the timing and extent of damage. When trees located in potential avalanche-starting zones die off because of fire or disease, avalanche activity may be enhanced, with downslope forests subject to damage. Humans alter avalanche size and frequency in a few limited locations above highways and ski areas for safety reasons. However, there is little that humans can or should do about the forest alterations caused by avalanches. In the context of the Sierra Nevada Ecosystem Project, avalanches are a forest influence that must be considered, but they are not a management or policy concern.

FLOODS

Floods are merely events of higher than average stream flow in response to storms or other large inputs of water. Generally, high-flow events that rise above stream banks are the phenomena of concern. Considering the overwhelming role of snow in the hydrologic cycle of the Sierra Nevada, snowmelt floods are the most obvious source of peak flows. Snowmelt floods are an annual event each spring of sustained high flow, long duration, and large volume. However, they usually do not produce the highest instantaneous peaks. The Sierra Nevada snowpack at the maximum of winter accumulation represents an enormous reservoir of potential runoff. The sustained input of water into reservoirs and canals can overwhelm storage and conveyance capabilities and can cause substantial leakage through levees (Dean 1975). Particularly large snowmelt floods in Sierra Nevada rivers have been documented in 1906, 1938, 1952, 1969, 1983, and 1995. Although their peak discharges were generally less than twice the mean annual snowmelt flood and only one-tenth to one-half as great as the largest rain-on-snow floods, their total volumes were two to four times larger than average. In all cases, snow deposition was more than twice average amounts and persisted into April or May. Thus, snow cover was still extensive in late spring when energy available for melt was much greater than in early spring (Kattelmann 1990). There was substantial potential for serious snowmelt floods in 1995 with snow water equivalence almost twice average amounts at many sites. However, cloudy conditions during the spring and early summer limited the rate of snowmelt runoff generation so that instantaneous peaks were not exceptional. Nevertheless, the duration of moderately high water and the total volume of runoff were extraordinary.

Midwinter rainfall on snow cover has produced all the highest flows in major Sierra Nevada rivers during this century. In the past sixty years, six floods of large magnitude have occurred in almost all rivers draining the snow zone. Rainfall has occurred up to the highest elevations of the Sierra Nevada during winter, but the freezing level of winter storms generally fluctuates between about 1,000 m (3,300 ft) and 2,500 m (8,200 ft). Even during the warmest storms, snowpacks

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above 2,500 m (8,200 ft) rarely melt much because temperatures are close to freezing. The interaction of precipitation amount, freezing level, energy availability, and basin characteristics determines the relative response of rivers at different elevation zones. Large-magnitude warm storms do not seem to occur during spring in the Sierra Nevada. There are only a few moderate rain-on-snow events superimposed on spring snowmelt floods in the stream-flow record. Storms in April and May generally do not incorporate the warm air masses from low latitudes that lead to the warm storms that occasionally occur in the winter months (Kattelmann et al. 1991). In basins that are largely above 2,000 m (6,600 ft), the highest peaks also tend to be caused by rain-on-snow events, even though almost all the other floods in the annual series are of snowmelt origin.

Although the summer and early autumn seasons in the Sierra Nevada tend to be dry, a few minor storms or brief showers occur in most years (Hannaford and Williams 1967). In general, summer rainfall is much less of a flooding concern in the Sierra Nevada than in the Rocky Mountains (e.g., Jarrett and Costa 1982). However, subtropical storms occasionally move into the southern Sierra Nevada in late summer. Intense thundershowers occurring over a period of three or four days can generate local flooding, cause extensive surface erosion, and destabilize hill slopes. These storms may generate the greatest floods in some alpine basins that are sufficiently high to avoid midwinter rain-on-snow events and are oriented so that snowmelt rates are kept low because of northern exposure over much of the basin. In August 1989, a flood and debris flow generated by a thunderstorm in the 2,000 to 3,000 m (6,600 to 9,800 ft) headwaters of Olancha Creek in the southeast part of the Sierra Nevada damaged the Los Angeles Aqueduct several kilometers downstream at 1,200 m (3,900 ft).

The sudden release of water from storage generates the most extreme floods (Costa and O'Connor 1995) but occurs under a limited set of conditions in a small fraction of the Sierra Nevada. Although this type of flooding is localized, it may produce flood peaks that are at least several times greater than those caused by any other process, and it is likely to entrain large quantities of bed and bank material. Sierra Nevada lakes tend to be stable, with little risk of failure of their impoundments of bedrock or broad moraines. Failures of artificial dams were almost common during the hydraulic mining era. Recent dam failures in the Sierra Nevada include Hell Hole Dam on the Rubicon River in December 1964 (Scott and Gravlee 1968), North Lake Dam on a tributary to Bishop Creek in September 1982, and the coffer dam near Auburn on the American River in February 1986. A gigantic gate on Folsom Dam broke in July 1995 and allowed a large volume of water to be released but did not produce a high flood wave. The failure of landslide and snow-avalanche dams that temporarily impound streams undoubtedly occurs at a variety of scales in the Sierra Nevada, but large events of this type are not known to have been documented. Displacement of lake water by snow avalanches is yet another flood generation process in high-elevation streams of the Sierra Nevada (Kattelmann 1990, 1992). The impact of an avalanche on the ice cover of a lake can force large volumes of water into the outlet channel and affect aquatic organisms (Williams et al. 1993). These events may be relatively common and are the only means (other than earthquakes) of generating high flow immediately below lakes, which otherwise tend to attenuate floods.

These various flood-generation mechanisms modify stream channels to various extents. Although debate continues about the relative effectiveness of common events (e.g., annual snowmelt floods) versus catastrophic events (e.g., rain-on-snow events) in shaping the landscape (e.g., Wolman and Gerson 1978; Beven 1981; Costa and O'Connor 1995), large floods would seem to be particularly important in mountain streams because of the high proportion of material transported as bedload. In mountain rivers, rare high-magnitude floods are generally required to significantly alter the channel because material composing the bed and banks tends to be large and resistant to entrainment (Lisle 1987). However, the sequence of events of different magnitudes also determines the geomorphic effectiveness of particular floods (Beven 1981). Large floods that destabilize a channel can lead to enhanced sediment transport from low-magnitude events over several decades (Lisle 1987). Such effects have been documented in the Lake Tahoe Basin following extreme rain-on-snow or thunderstorm events (Nolan and Hill 1987; Glancy 1988). Similarly, two large rain-on-snow events in 1982 may have created channel conditions favorable for the high bedload transport measured in the snowmelt flood of 1983 (Andrews and Erman 1986). These interactions of different flood processes may be a critical influence on channel form and sediment transport in the Sierra Nevada.

Changes in channels as a result of floods have major impacts on aquatic and riparian communities (e.g., Swanson et al. 1982; Erman et al. 1988; Lisle 1989). Floods both flush fine sediments out of spawning gravels and deposit these fine sediments elsewhere depending on hydraulic factors and sediment supply. Riparian vegetation protects banks against erosion and aids in bank construction by enhancing deposition of sediment during overbank flows. Floods are often required for dispersal of propagules of riparian plants. However, shear stresses imposed by high flows often destroy riparian vegetation directly. Erosion of stream banks and excessive deposition of sediment also kill riparian plants. In meadows where the sod has been cut by vehicles or cattle, high flows can erode deep gullies, which consequently lower the local ground-water table and completely change plant composition. Catastrophic floods can initiate landslides directly above the channel that remove upland vegetation. These various actions cast floods in the role of a disturbance mechanism with regard to terrestrial communities. Fortunately, riparian vegetation tends to become reestablished quickly if adequate soil water is available (e.g., Gregory et al. 1991). Riparian vegetation tends to survive routine flooding (magnitudes that occur up to once in five or ten years on the average). Rare, high-magnitude events have the potential to alter large portions of riparian communities.

Modest changes in forest cover tend to have little measurable effect on flood generation (Hewlett 1982). Where trees are harvested, transpiration is reduced, and there is less soil moisture deficit that could otherwise store potential runoff from storms. Therefore, streams can rise more quickly and receive greater volumes of water in areas devoid of trees than in forests. However, such effects tend to be local under conventional forest practices. If forest vegetation is converted (long-term change with little opportunity to recover to its original state) to sparse and/or shallow-rooted vegetation (or pavement at the extreme) over a large fraction of a watershed, then there is potential for greater effects. Increases in peak flows resulting from forest harvesting tend to be most noticeable in the early part of the rainy season and during small storms. During major storms, almost all available soil moisture storage is filled under all vegetation types, and rates of runoff production from all lands become similar (Hewlett 1982). In larger rivers, floods are a product of water volumes received from tributaries. The synchronization of incoming flows determines the flood level, and the original runoff generation processes on the landscape become irrelevant. There is no evidence to suggest that peak flows in larger streams have changed in the Sierra Nevada as a result of forest management activities. Although such increases may have occurred, we lack the data to demonstrate a change. In creeks influenced by urban and suburban development, flood magnitudes have probably increased as a result of increases in impermeable surface, but flow records have not been located to quantify such impacts. Channels generally increase their cross-sectional area to accommodate persistent increases in flood size such as can be expected following urbanization (Dunne and Leopold 1978). Water management activities, particularly the construction of large dams, have dramatically reduced flood magnitudes throughout the range.

If forests are replaced by shallow-rooted vegetation over a large proportion of a basin, then floods can be markedly increased. The greatest danger of such a widespread change would be from catastrophic fire. Intense fires can also create hydrophobic layers within the soil, which dramatically increase runoff (Anderson et al. 1976). In the snow zone, widespread reductions in forest density and/or forested area would tend to increase the local rate of snowmelt and advance the local timing of snowmelt runoff. The effect of such changes on spring peaks in stream flow would depend on the relative timing and synchronization of tributary peaks under present conditions (Anderson 1963). In smaller basins within the forested zone, the current slow rate of snowmelt runoff from forested areas tends to spread the seasonal hydrograph over several weeks. Changing forest to clearings would compress the snowmelt season, and, if enough area were cleared, flood peaks could be expected to increase. In larger basins, the earlier melting of snow in the former forest might lower water levels during late spring when the alpine snowmelt contributions would be at a maximum. The snowmelt runoff regime of the Sierra Nevada could be further affected by interactions of changes in both vegetation and climate.

Floods are commonly described in terms of their magnitude and frequency—how big they are and how often a flood of a particular size has been observed or is likely to occur. Flood magnitude at a particular point is expressed as discharge—volume of water over a time interval (usually cubic feet per second)—or as stage—height of the river surface on a fixed rule (or distance below a bridge). Estimating the frequency of a flood with a particular magnitude depends on availability of records of floods over time. If we have 100 years of recorded stream flow at a point on a river, we can identify the ten largest floods in that century, for example. The magnitude of the smallest of those ten floods was exceeded ten times in that century, or once every ten years on the average. We can call the flood of that size a "ten-year flood" and expect that a flood at least that big has a 1 in 10 chance of occurring in any particular year. The likelihood of floods of other sizes can be estimated in a similar way. Some relatively simple statistical procedures are used to refine these estimates, especially for rare floods, for which the observed record is generally too short. Flood frequency must be considered over a long time span. In general, floods should be considered as independent of one another. The qualifying phrase on the average is critical. Floods exceeding the ten-year level could occur twice in the same year or perhaps be thirty-five years apart, but 1,000 of them would be expected in 10,000 years.

Floods become natural hazards when they interact with people and our structures and activities. These natural hazards occur on floodplains. The hazard posed by floods could be avoided entirely by avoiding floodplains during floods. Floodplains are essentially parts of rivers that are occupied by flowing water on the occasions of floods. If our society incorporated that definition in our collective development plans, we would experience much less trouble during those occasions. An individual considering construction of a house "on a floodplain" would be much less likely to want to build a house "in a river." However, modern society has often ignored such considerations and extensively developed floodplains instead. In years like 1995, we are reminded that some people have built in a river. In 1995, 53 of California's 58 counties qualified for "disaster assistance" after the floods of January and March. Communities within the Sierra Nevada did not sustain damage comparable to those in the Sacramento area or the Coast Range, but several were threatened by high water. All lands adjacent to streams that have been inundated before are at risk in the future.

Floodplain occupants have long set public policies that effectively subsidize that occupancy. Structural attempts at flood control such as dams and levees and broad financial compensation for flood damages are generally paid for by the vast majority of taxpayers who do not live anywhere near a stream.

Development on floodplains creates political pressure to build more flood control reservoirs upstream at the expense of nature and the nation. The new flood-control structures inundate additional river channels, riparian corridors, and deep canyons. Despite its enormous environmental and financial costs, the Auburn Dam was again being promoted as a means of protecting occupants of the American River floodplain after the storms of 1995 raised concerns. Nevertheless, after the 1993 floods on the Mississippi and the 1995 floods in California, there are signs that flood policies may be changing. Agencies at various levels of government are beginning to purchase land on floodplains as a cheaper alternative to paying for recurring damages or giant new dams. Such expenditures were rarely questioned until society began to view flooding as a natural, normal process of rivers that occurs in locations that are easy to recognize and can be avoided instead of a disaster that strikes the unlucky. Ideally, any construction on floodplains must be designed with the risk of flood damage clearly in mind—design the structure to avoid or withstand floods of a particular magnitude, anticipate and accept the eventuality of damage or loss, or relocate upslope. Often the risk of damage involves more than just damage to the structure itself. Failure of inadequate culverts or bridges can lead to massive amounts of bank erosion. Toxic chemicals stored in structures on the floodplain can be released into the stream. Pieces of structures destroyed by the flood and transported downstream can damage other structures and vegetation. It is to be hoped that the floods of 1995 will provide incentives for individuals, communities, and agencies to begin some real floodplain management.

AVALANCHES

Snow and avalanches are important influences on forests of the Sierra Nevada. In the forested snowpack zone (above about 1,500 m [4,900 ft]), snow insulates the soil against freezing and extends availability of soil water for weeks beyond the winter precipitation season. Snow is also responsible for mechanical damage to trees by overloading branches intercepting snowfall, trimming off limbs caught within the snowpack as it settles, bending and breaking trees as the snowpack slowly creeps (deforms) or glides downslope, and snapping limbs and trunks during avalanches (Salm 1979; Wakabayashi 1979).

Avalanches may be defined as rapid downslope movements of snow. They can range from a few snow grains rolling a few centimeters to immense volumes of snow falling thousands of meters with tremendous impact pressures. After snow crystals precipitate from the sky, they tend to lose their complex shapes and become semirounded grains, bonding with other grains in the process. Snow layers from individual storms constitute a snowpack that evolves over time. Grains within a storm layer tend to form stronger bonds with one another than those at the interface between layers, thus forming a cohesive slab of snow that acts as a structural unit with possibly poor bonding to the underlying layer. The force of gravity imposes mechanical stresses within a snowpack. If these stresses exceed strength at some point, local failure occurs. After such a failure, adjacent areas receive additional stress and are either strong enough to withstand it or fail in turn, possibly leading to propagation of the failure over a large area and release of an avalanche. The balance between stress and strength within the snowpack is extremely complex. In general, snowpack strength increases as bonds grow between grains, reducing the risk of an avalanche soon after a storm ends (Perla and Martinelli 1976). Avalanches can also occur when strength decreases in the presence of liquid water. When high-elevation snowpacks initially get wet in spring, bonds between layers can weaken and avalanches occur without an increase in stress (Kattelmann 1985). Rainfall on a snowpack can both increase stress by adding weight and decrease strength. Wet snow avalanches can occur on shallower slopes than dry snow avalanches.

In the Sierra Nevada, the vast majority of avalanches occur during and shortly after storms. If loading of new snow increases stress at a rate faster than strength develops, the slope will fail. Intense snowfall (greater than 25 mm [1 in] per hour) and high winds redepositing snow increase the load much faster than typical storms, so avalanche activity is enhanced during severe storms. Critical stresses develop more quickly on steeper slopes and where deposition of wind-transported snow is common. Consequently, certain slopes are prone to avalanching during almost every storm while most terrain simply is not steep enough or never accumulates enough snow to fail. Between these extremes is a continuum of terrain conditions that require increasingly severe (and rare) weather and snow conditions to produce an avalanche. Therefore, while some avalanche paths consistently run several times each winter, other areas may slide only under unusual sets of conditions that occur perhaps once in a hundred or a thousand years. Such extreme situations produce massive avalanches over much of the Sierra Nevada.

Our short and geographically limited records (and even shorter memories) of weather in the mountains provide little basis for anticipating the potential of major avalanche cycles. For example, storms in late March 1982 resulted in a very destructive and tragic avalanche cycle. Press accounts called it the "storm of the century" even though greater snowfall quantities for various time intervals had occurred at least four times in the previous two decades (Stetham 1992; Osterhuber 1993). Less than four years later, precipitation totals for one, two, three, and four days during a series of severe storms were more than 1.7 times greater than previous records. Nevertheless, avalanches in the Alpine Meadows area near Lake Tahoe did not even approach the size of those generated in 1982, while elsewhere in the Sierra Nevada, damage was extreme (Wilson 1986). The winters of 1993 and 1995 left exceedingly deep snowpacks but did not produce catastrophic avalanches.

Avalanches occur throughout the snow zone of the Sierra Nevada but become more common with increasing elevation and steeper slopes. Because prevailing wind direction during storms is from the southwest, snow is scoured from south- and southwest-facing slopes and redeposited on north- and northeast-facing slopes, with consequent differences in avalanche occurrence. The greater solar radiation input and higher temperatures on south-facing slopes tend to stabilize those slopes faster than shaded slopes. The influence of avalanches on forests generally increases with increasing elevation up to local timberline. Starting zones of avalanches (places where avalanches begin) are usually above timberline, but the slides continue into the trees below. Red fir and lodgepole pine forests are probably impacted the most, but some avalanche paths extend into the upper mixed conifer zone. Subalpine trees such as mountain hemlock, foxtail pine, and whitebark pine generally occur outside avalanche paths, which run more frequently at higher elevations and do not allow the trees to become established. Avalanche paths in the Sierra Nevada have been mapped only in existing and proposed ski areas, highway and rail corridors, and mountain communities where the forest, terrain, and avalanche hazard might be managed. For example, avalanche path mapping identified forty-nine paths in a 21 km^2 (8 mi^2) area of the Galena Basin, the site of a proposed ski area northeast of Lake Tahoe (Frutiger 1990).

Avalanches can be a dominant influence on plant community structure and create a fragmented vegetation mosaic (Patten and Knight 1994). In the forest zone, avalanche paths are easily recognized as strips oriented straight down the hill containing a different age or type of vegetation than that adjacent to the strip (Martinelli 1974; Mears 1992). These vertical paths through the forest are particularly obvious when the strips are devoid of vegetation or contain deciduous trees. Aspen and other fast-growing, light-tolerant trees often colonize avalanche tracks. A series of avalanches may progressively force a path through a forest stand. After a clear path is established, a major avalanche can break through and continue into a previously untouched forest (Perla and Martinelli 1976). A thick jumble of debris can remain in the runout zone for decades if undisturbed. Such debris could potentially influence other disturbance factors such as fire, insects, or disease. Conversely, fire and insect kill can allow avalanche paths to develop that would not had the forest remained alive (Fohn 1979).

Vegetation in the avalanche path can be used to infer the size and frequency of avalanches (Perla and Martinelli 1976; Wakabayashi 1979; Mears 1992). If an avalanche occurs at least every decade, its path will be free of trees or include a few large individuals with obvious damage. Shrubs and flexible trees up to a couple of meters in height may be present. Where an avalanche has not occurred for up to thirty years, aspen and small conifers may occupy the path. Larger conifers of uniform age but younger than the adjacent forest may be found where avalanches have not occurred for several decades. Branches of the older trees along the borders of the path are usually missing. If paths above timberline avalanche infrequently, a forest can recover between major avalanches. These extreme events can occur on a timescale similar to the growth of a mature stand (deQuervain 1979). A single avalanche in Switzerland in 1962 destroyed about 100 ha (250 acres) of mature forest (Fohn 1979). Loss of productivity of forest land is considered an economic cost of avalanches (Voight 1990). However, little commercial forest is known to be impacted by avalanches in the Sierra Nevada because the most productive forests are generally found in lower-elevation terrain not particularly prone to avalanches. At higher elevations, several hundred hectares of forest were destroyed by avalanches in 1986 (Wilson 1986). A large proportion of these trees were 125–150 years old. Some trees destroyed near Sonora Pass were 350 years old.

Forests offer a substantial protection role with respect to avalanche hazard. This function was formally recognized in 1876 when Switzerland enacted a forest protection law to maintain forests above inhabited areas and to reforest places that might provide protection from avalanches (Armstrong and Williams 1986). Forests influence snow in a variety of ways. Canopies intercept and retain snowfall. Some of this snow sublimates, some melts and drips into the snowpack below, and some just falls off as clumps that are often wet. Besides reducing the amount of snow compared with adjacent open areas, interception ultimately leads to strengthening the snowpack around the tree. The drip and snow falling from branches form a rim around the vertical projection of the crown, which significantly increases the overall strength of the snow in the forest compared to the stems alone (Gubler and Rychetnik 1991). Forests also tend to disturb stratification of the snowpack, break up weak layers, increase density, and minimize surface hoar (which can become an extremely weak layer within the snowpack if buried by snowfall). Under extreme conditions, avalanches can start in openings within the forest as small as 30 m (100 ft) long and 15 m (50 ft) wide (Gubler and Rychetnik 1991).

Avalanches also produce a variety of geomorphic effects, such as scouring of vegetation and soils from hill slopes, maintenance of vertical troughs, accumulation of debris in the runout zone, and creation of impact and scour pits (Davis 1962). When avalanches dam streams, serious floods and channel damage may occur following eventual failure of the snow dam (Perla and Martinelli 1976; McClung and Schaerer 1993). Avalanches also generate floods by suddenly displacing water from lakes. Avalanches can even affect fisheries. For example, formation of a plunge pool in a lake by avalanches provided a high-quality spawning area for brook trout by transporting gravel and removing floculent organic matter from the hatching area (Williams et al. 1992).

Avalanches are defined as a hazard when they influence human activities. In the Sierra Nevada, avalanches did not have as great an effect on nineteenth-century mining as in the Wasatch and the Rockies, where avalanche tragedies were common (Armstrong and Williams 1986). Until after World War II, very few people occupied the higher portions of the Sierra Nevada in winter. Rapid growth of winter recreation put many people at risk. Ski areas remain the principal foci of avalanche hazard where the steepest runs are avalanche paths that require artificial control. Control usually implies an explosion to trigger release of an avalanche at a time when the path is empty. The force of an explosion usually propagates only a short distance and ruptures critical bonds under a slab. As more roads were maintained in winter, more travelers were exposed to avalanches. Avalanche paths cross Highways 4, 50, 80, 88, 89, 158, and 395 as well as many local roads in mountain communities. Highway closure during periods of avalanche danger is a major indirect cost of avalanches (Voight 1990). Control via hand charges, artillery, and, recently, propane-fueled exploders (GazEx) on California Highways 50, 88, and 158 and Nevada Highway 431 allows roads to be open sooner during storms. Rapid expansion of mountain communities led to construction of vacation and year-round residences in avalanche paths. In recent years, homes and other structures have been damaged or destroyed at Virginia Lakes, Twin Lakes, and Long Valley, and near Tahoe City. A fatal avalanche occurred within a residential area of Mammoth Lakes in 1993. The large avalanche cycles of 1982 and 1986 led several Sierra Nevada counties to consider zoning and other land-use restrictions to reduce avalanche hazards (Penniman 1992). However, property owners and real-estate interests vigorously fought such restrictions, and the counties concerned have settled on some form of a "fair warning" to owners and renters within avalanche zones. Placer County requires that new construction in avalanche areas be designed to resist avalanche forces (Placer County 1994). Washoe County has ignored the recommendations of its consultants and has taken no action, raising liability concerns when damage eventually occurs (Penniman 1992). The lack of agreement between avalanche consultants in defining hazards on the ground has impeded avalanche zoning efforts (Penniman 1992) and is another example of the perils of scientific uncertainty in developing public policy.

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