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DEBRIS BASIN POLICY AND DESIGN

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ABSTRACT

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Debris flows cause considerable property damage and loss of life. The debris basin is a widely used control alternative, for which accurate design methods are not available. Thus, there is a need for a systematic design procedure, as well as a practical basis for establishing policy elements. A design procedure that accounts for seasonal volumes of debris is presented. The choice of the design return period and burn interval, both of which are important policy elements, is a function of the hazard level associated with failure. The monitoring and maintenance of debris basins are also important policy elements. The frequency of monitoring a basin to ensure adequate storage is a function of the potential hazard presented by a debris flow to the area downstream of the basin, as well as the precipitation, the frequency of burning in the watershed, and the drainage area. A procedure for estimating the temporal accumulation of debris is presented so that public agencies will know when to monitor and dredge each debris basin in their jurisdiction. The adoption of rational design methods and policy elements relating to debris basins should minimize the risk of failure of the basins.

INTRODUCTION

Debris flows are of interest in engineering because they are a naturally occurring hazard to both people and the public infrastructure and often require structural measures for control. The term 'debris flow' refers to the mass movement of a mixture of granular solids, water, and air. The composition of the flow may vary, but a flow typically contains a significant portion of cobbles and boulders. While nonstructural control measures are appropriate in a debris flow control policy, structural facilities appear to be the most reliable control measure, with the debris basin being the most widely used structural measure for watershed protection.

In the southwestern U.S., especially southern California, and Japan, various types of structural methods have been used in attempting to control debris flows. Channel improvements have proved ineffective because channels quickly become blocked causing the debris to take different flow paths (Waldron, 1967). Waldron also described the failure of six small check dams

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that were designed to retard the debris flow rate; when they were nearly completed, the dams were destroyed by a debris flow. Hollingsworth and Kovacs (1981) discussed the following control methods: retaining, deflection or stem walls, debris basins, and debris fences. Retaining, deflection, and stem walls are used for the protection of individual buildings such as private homes. Debris fences are used to retard the flow rate of the debris flow and break up the flowing mass. The improper placement of these fences usually results in failure. Debris basins are often constructed at the base of narrow canyons with the walls of the basin found in the bedrock of the canyon walls.

The failure of a debris basin is usually the result of an insufficient capacity such that the basin cannot contain the incoming debris flow. The design of existing debris basins has often been based on the volume of a previous single debris flow rather than on the basis of the potential magnitude of a future seasonal event. A single debris flow occurs as one event whereas a seasonal event is the volume of debris that may collect in a basin during an entire rainy season. This problem is compounded by a lack of data by which to determine the largest past event. The computation of volumes for existing basins has also been estimated from biased models; the models were based on ratio correlation (Benson, 1965) and log transforms of data (McCuen et al., 1990a). Because of inadequate designs, debris basins may fail. Such failures have been reported in the western U.S. (Rice and Foggin, 1971; Costa and Jarrett, 1981; Keefer et al., 1987).

Maintenance of debris basins is extremely important since the risk of failure increases when debris is allowed to accumulate in the basin. A basin cannot function as designed if it is not properly maintained, i.e. it is allowed to fill with sediment and debris.

To serve as an effective control measure, the design and maintenance of debris basins should be regulated with a comprehensive policy statement. The policy should specify a design method that is systematic, computationally efficient, based on actual experience reflecting the probability of future occurrences, and which allows for variation in important casual factors. The policy must also include a section on maintenance since the probability of failure increases with a poorly maintained storage facility. Finally, policy elements should address the issue of the creation of a potential hazard downstream by failure of the structure to contain a debris flow.

The objectives of this study were to develop a design procedure based on expected volumes of debris for a given seasonal event and hazard level and to propose a systematic monitoring procedure to assess the need for maintenance of the basins. The design method, monitoring program, and maintenance requirements form the central core of any policy statement.

HAZARD POTENTIAL

The term 'hazard' refers to an exposure to harm or loss, with the implication that the threat is posed by chance or is largely beyond control. The variation in hazard potential that is associated with engineering structures has led to differences in factors of safety applied to similar design problems, as well as other design standards and criteria. This is true in earth dam classification, for example. Dams for waterflood control are classified for a variety of reasons, including the following: (1) to select the criteria for design; (2) to identify dams that should be given priority in dam inspection; (3) to provide compatibility between guideline requirements and involved risks; (4) to provide an indication to concerned citizens of the potential hazard. Other factors, which are somewhat more difficult to quantify but just as important, are the effect of failure on public confidence, state and local regulations, and the responsibility of the public agencies involved (Soil Conservation Service (SCS), 1976). Dams can be classified according to size, which includes both the storage volume and height, and the hazard potential. While different classification systems exist, they are often based on similar concepts. In their dam structure program, the Soil Conservation Service (SCS, 1976) established a system with three classes that is based on the potential for the loss of life and the disruption of services. The Corps of Engineers (USCE, 1975) classifies dams according to size and hazard potential, with size dependent on height, and storage volume and hazard potential dependent on the loss of life and economic loss.

Policies regarding debris basin design, maintenance, and monitoring should be a function of the potential hazard to the area below the basin that failure of the basin would represent. The hazard level may be categorized according to loss of life, loss of service, and economic loss as shown in Table 1.

Each jurisdiction must decide on a hazard level that is appropriate for the particular area of concern. If the area is highly developed, then a high hazard level is appropriate. This level will then be a factor in both design and maintenance decisions. A high hazard level will require a larger design volume of storage and more frequent monitoring and dredging in order to ensure the safety of the community below the basin. A basin to be located above a low hazard area will require a smaller volume of storage and less frequent maintenance.

Two major policy elements, which can be varied to reflect the hazard level, in designing the volume of a debris basin are the exceedence frequency of the debris flow event and the burn interval. The burn interval is either the length of time from the most recent significant fire that destroyed at least 40% of the vegetal cover or a policy variable that reflects a period of time between significant burns. Large return periods for the seasonal debris flow volume and short burn intervals should be used for design and maintenance at high hazard locations; McCuen et al. (1990b) showed that these conditions are associated with the smallest risk of failure. Small return periods (i.e. 2-year and 5-year) and long burn intervals (i.e. > 10 years), which are associated with relatively high risks of debris basin failure, can be used at low hazard locations. The hazard potential should also be used when developing policy elements for the maintenance of debris basins.

TABLE 1

Hazard classification criteria for debris basins

Hazard level loss	Criteria used		
	Loss of life	Loss of service	Economic
Low	None expected (no permanent structures in hazard zone)	None or possibly minor roadways	Minimal
Moderate/ appreciable	Few possible (isolated homes or light industry in hazard zone)	Possibly brief interruption of major highways or service of noncritical public utilities	
High/ excessive	More than a few	Serious damage to important public utilities and major highways	

ESTIMATING DEBRIS VOLUMES FOR DESIGN

In general, there are two types of design problems, with one type based on seasonal volumes and the other based on single event volumes. The design of facilities in which debris is stored, such as debris basins, should be based on estimates of seasonal volumes of debris because it would be impractical to dredge a debris basin after each debris event owing to limited resources and because of the physical difficulties in dredging wet debris. However, the design of bridge openings and the delineation of debris flow hazard areas (similar to waterflood floodplain zoning) should be based on single-event debris volumes. Thus, there is a need for methods to estimate both seasonal and single-event debris volumes.

Seasonal debris volumes

Given regional debris volume data, regionalized prediction equations can be developed by subjecting the debris data for each station to a frequency analysis, obtaining estimates of debris volumes for selected return periods (T), and then relating the T-year estimates to watershed characteristics using statistical modeling methods. Separate analyses can be made for volumes of different durations, with seasonal and single event volumes of general interest. Volumes of debris may be estimated for return periods of 2–100 years. This is a seasonal debris flow return period and should not be confused with the return period for rainfall. The 100-year storm does not necessarily correspond to the 100-year seasonal debris flow event. The following prediction equations were developed for small watersheds (less than ~2 mile^2) in southern California (Johnson et al., 1990), including Los Angeles, Orange, and San Bernadino Counties using measured data collected from existing debris basins located in such canyons as Harrow, Bailey, Bradbury, etc. in Los Angeles County:

$$Y_2 = 485\, B^{-0.24}\, R^{0.75} H^{0.11} \tag{1a}$$

$$Y_5 = 675\, B^{-0.24}\, R^{0.93} H^{0.19} \tag{1b}$$

$$Y_{10} = 795\, B^{-0.24}\, R^{1.03} H^{0.26} \tag{1c}$$

$$Y_{25} = 940\, B^{-0.24}\, R^{1.13} H^{0.35} \tag{1d}$$

$$Y_{50} = 1080\, B^{-0.24}\, R^{1.20} H^{0.42} \tag{1e}$$

$$Y_{100} = 1225\, B^{-0.24}\, R^{1.26} H^{0.48} \tag{1f}$$

where Y_T is the yield (in yd^3 mile^{-2} year^{-1}) for a return period of T years, B is the number of years since the most recent forest fire in which at least 40% of the watershed burned, R is the relief ratio (in ft mile^{-1}), and H is the value of the hypsometric index expressed as a decimal. There were few data for those fires which burned < 40% of the watershed. Therefore, only those events where > 40% burned were included in the study. The relief ratio and hypsometric index were both found to be important factors in debris generation. Soil and rock types are accounted for by the coefficients of eqn. (1). The range of soil types in this region was too limited to include in a regression. The development of these equations is described further by Johnson et al. (1990). Before eqn. (1) is used in any area outside southern California, an analysis on the applicability of the equation including the soil and rock type should certainly be undertaken.

Equation (1) provides seasonal volumes for debris flow recurrence intervals rather than volumes for a single event. To obtain the design volume of storage, V_s, of a debris basin for a particular watershed, the yields from eqn. (1) are multiplied by the watershed area and by the fraction of a year during which debris flows typically occur, which is approximately the length of the rainy season, possibly 0.3–0.5 years. When applying eqn. (1) in design, the burn interval should be obtained from the local policy. In setting the policy, a short burn interval should be used where fires are frequent. Fires from both electrical storms and vandalism should be considered in setting the policy burn interval. The selection of a short burn interval will result in a relatively large computed volume of debris. The debris basin will provide adequate storage for debris flows during an average rainy season for the specified return period. If funds for more frequent dredging are available and the debris basin will drain in a short period of time such that dredging is possible, then a fraction less than the duration of the rainy season can be used.

As an example of the use of eqn. (1), Zachau Canyon watershed has an area of 0.35 mile^2, a relief ratio of 1482 ft mile^{-1}, and a hypsometric index of 0.38. The results of applying eqn. (1) for burn intervals of 2 and 10 years and season

TABLE 2

Design debris yields for Zachau Canyon[1]

Recurrence interval	Burn interval (years)			
	0.3-year season		0.125-year season	
	2	10	2	10
2	9000	6000	3800	2500
5	45000	30000	19000	12500
10	102000	69000	42500	29000
25	229000	156000	95000	65000
50	410000	280000	171000	117000
100	680000	464000	283000	193000

[1] Area – 0.35 mile^2; relief ratio – 1482 ft mile^{-1}; hypsometric index – 0.38.

lengths of 1.5 months (0.125 years) and 0.3 years are given in Table 2. This range of volumes corresponds to 0.01 ft of erosion for the smallest 2-year event to 1.9 ft for the largest 100-year event.

Single event debris yields

Part of the data base that was used to generate eqn. (1) consisted of volumes of debris and sediment that accumulated over very short periods, usually 30

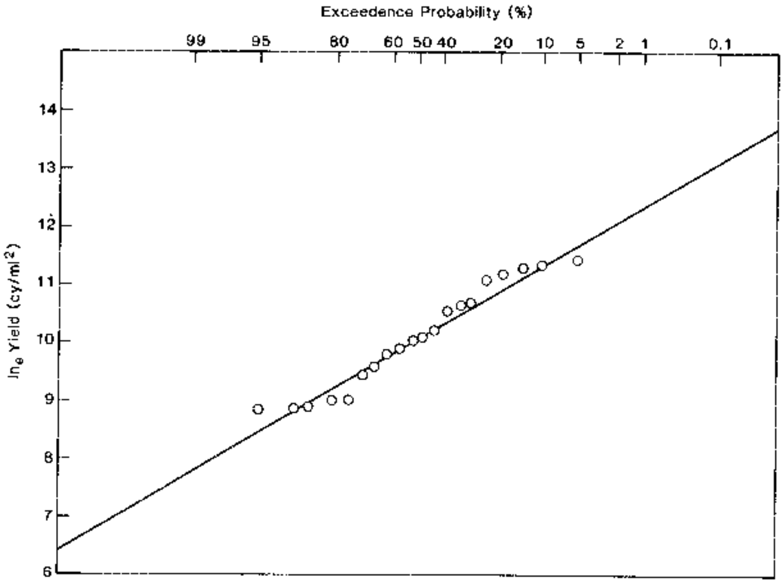

Fig. 1. Log-normal frequency distribution of debris flow data for 20 individual storms.

days or less. When these data were grouped with the remainder of the data base, they consistently departed from the general trend. This suggested that they represented a different underlying population. However, the data could not be ignored since the accumulated volumes were significant. These data were identified as resulting from individual storm events so the data were used to develop a model for estimating volumes of event-based debris. The data were subjected to a frequency analysis, with the trend suggesting a log-normal distribution. Figure 1 shows the log-normal distribution of the measured debris data for single events. From this plot the expected yields ($\text{yd}^3\,\text{mile}^{-2}$) for the 2-, 5-, 10-, 25-, 50-, and 100-year return periods were obtained.

The ratio of the single event design volume to the seasonal volumes of eqn. (1) were computed for 29 watersheds in Los Angeles County. The seasonal volumes were computed using eqn. (1) with average burn intervals of 2, 4, and 10 years, season lengths of 1.5, 3, and 6 months (0.125, 0.25, and 0.5 years, respectively), and the actual values of R, H, and the drainage area. The average ratios f were determined for each return period and used to calibrate the following equation:

$$f = \exp\left[-1.100\left(S - \frac{1}{12}\right) + 0.002(T - 2)\right] - 0.114\,(B - 1)^{0.060}\left[\left(S - \frac{1}{12}\right)^{0.033} + (T - 2)^{0.382}\right] \quad (2)$$

where S is the length of the season as a fraction of a year, T is the return period in years, B is the burn interval in years, and f is a dimensionless factor for determining the approximate single event volume given the seasonal volume. Equation (2) is valid for $1/12 \leqslant S \leqslant 0.5$ years, $2 \leqslant T \leqslant 100$ years, and $1 \leqslant B \leqslant 10$ years. The value of f can be used to estimate when a debris basin should be dredged, as described below in the discussion on monitoring. For policies that specify short seasonal periods, the expected volume for a single debris flow is not much different than the seasonal design volume, especially for short return periods. When using eqn. (2) for design, the values of S, T, and B should be the same as those used for the seasonal design.

A MONITORING AND MAINTENANCE PROCEDURE

In order to minimize the risk of failure of a debris basin, the basin must be maintained. A basin that is not maintained will not function as intended by the designer. The removal of accumulated debris and sediment is the primary maintenance requirement. Therefore, the material within the basin must be periodically dredged so that the design volume is available to control future debris flows. A basin must be monitored to ensure that accumulated debris and sediment is not so great as to significantly increase the risk of failure. It may also be necessary to dredge the basin following heavy rainfalls (greater than

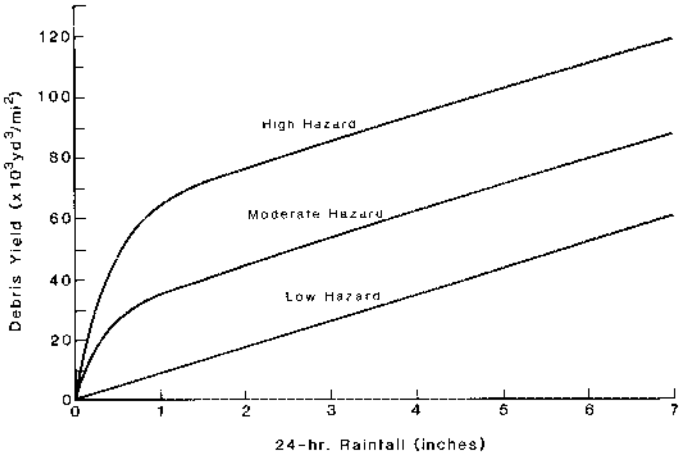

Fig. 2. Debris yields for various hazard levels.

the 2-year storm). A monitoring method that will indicate the need for maintenance has been developed using the measured data from debris basins in the southern California region.

Real-time estimation of debris accumulation

A model for real-time accumulations A_r was developed by regressing the debris yield (in $\mathrm{yd}^3\ \mathrm{mile}^{-2}$) on the 24-h rainfall depth (in):

$$A_r = 6600\ P^{1.158} \tag{3}$$

The standard deviation of the debris yield A_r of eqn. (3) is 29 000 $\mathrm{yd}^3\,\mathrm{mile}^{-2}$, the standard error of estimate is 21 000 $\mathrm{yd}^3\,\mathrm{mile}^{-2}$, and the correlation coefficient is 0.67. Figure 2 shows a plot of this equation, which is indicated as being appropriate for low hazard areas. Curves representing appropriate yields for high and moderate hazard levels were formed by computing the upper 99 and 80% confidence intervals of eqn. (3), respectively. The variation between hazard levels reflects the sampling variation of the estimation method.

Monitoring

For any storm event during which a significant rainfall occurs, the volume of debris that has accumulated in the basin should be measured during an on-site visit. In the event that this is not possible (because of storms, inadequate funds, etc.), the amount of debris that accumulates in a basin may be estimated using the debris yield for the appropriate hazard level from Fig. 2, with the value multiplied by the watershed area to obtain a volume in yd^3. When rain occurs on consecutive days, the largest 24-h depth should be used

TABLE 3

Factors for determining the portion of the design volume filled by a single debris flow event

Day	Rainfall (in)
1	0.05
2	0.23
6	0.12
7	1.68
8	1.80
17	0.20
19	0.01
23	0.72
24	1.10
25	4.20

to indicate the expected volume of a debris event. Analysis of the Los Angeles data suggested that it would be reasonable to assume that a new event begins after more than 7 days of no rainfall. The total accumulation of debris in the basin is then the sum of the real-time estimates obtained with Fig. 2. As an example, consider a hypothetical watershed of 0.4 mile^2 with a moderate hazard level and for a 25-day period with the rainfall depth as given in Table 3. From Fig. 2, a debris yield of 43 000 yd^3 mile^{-2} is obtained for the first 8 days using the largest 1 day rainfall of 1.8 in; thus, the volume is:

$$(43\,000\ \text{cy mile}^{-2})\ (0.4\ \text{mile}^2)\ =\ 17\,200\ \text{yd}^3 \tag{4}$$

After a dry period of 8 days the debris yield of 63 000 yd^3 mile^{-2} is obtained for days 17 25 using the rainfall depth of 4.2 in; thus, the volume is:

$$(63\,000\ \text{cy mile}^{-2})\ (0.4\ \text{mile}^2)\ =\ 25\,200\ \text{yd}^3 \tag{5}$$

Therefore, the total debris yield for the 25-day period is 42 400 yd^3.

The procedure for estimating the volume of debris accumulation with Fig. 2 assumes that there has not been a significant burn on the watershed. Since a burn will significantly increase the volume of the debris yield, the estimated volumes should be adjusted by some factor that reflects this increase. The debris yield estimates obtained with Fig. 2 should then be multiplied by 5 or some other value set by policy as discussed below, during the first year following the fire to account for the additional expected accumulation. During the second year following the fire, the burn factor can be reduced to 2 as recovery of the watershed vegetation has already begun (Helvey, 1980; Johnson et al., 1990). Use of the burn factor of 2 should be continued until the watershed has nearly recovered, which occurs about 5–10 years following a burn (Helvey, 1980; Wells, 1981; Johnson et al., 1990).

The purpose of monitoring is to decide when a debris basin will be inspected and dredged. Equation (3) and Fig. 2 provide a method of estimating how much debris might accumulate in the basin during a particular storm. This monitoring method, however, provides no guidance regarding the appropriate level at which to dredge the basin. In developing a policy, it is necessary to establish a criterion. One possible criterion would be to allow debris and sediment to accumulate in the basin until there is just sufficient capacity to hold the volume generated during a single event having the same return period as the seasonal design volume used for design with eqn. (1). If the single event design volume is obtained using the appropriate coefficient from eqn. (2), then a volume equal to V_s $(1 - f)$ could accumulate in the basin, with sufficient volume fV_s remaining to hold one event for the same return period. In using eqn. (2), the same return period, burn interval, and season length should be used as were used for the seasonal design volume. Since a basin designed for a 2- or 5-year return period is designed to hold a relatively small volume of debris, it should be expected that these basins will need to be dredged more frequently than basins based on 25- or 50-year return periods. For values of f close to 1, it should be expected that the basin may have to be dredged frequently. When the estimated volume of sediment in the basin, as computed with Fig. 2, reaches this volume (i.e. V_s $(1 - f)$), the policy should require on-site inspection of the basin. If the actual volume of sediment upon on-site inspection is greater than the allowable limit, then the basin should be dredged. However, if the actual debris accumulation in the basin is less than the allowable limit, then the estimated accumulation should be replaced by the actual volume in the basin; the procedure described above should then be continued until the estimated volume again reaches the maximum allowable accumulation, at which time an on-site inspection of the basin should be made.

POLICY RECOMMENDATIONS

In order to ensure the safety of the community downstream from a debris basin, design standards and maintenance policies must be established by local jurisdictions. A policy should address factors involved in the design of the basin such as the period over which debris is expected to be deposited in the basin during the course of a year and the selection of both an appropriate return period for the seasonal debris volume and the burn interval. A policy should also establish maintenance requirements such as the frequency of on-site inspections and dredging of the basin.

When developing a policy, the selection of the return period of the seasonal debris volume and the design burn interval should be a function of the potential hazard. The risk of failure is greatest for a basin that is designed to control the debris flows having a short exceedence interval such as 2 years and an infrequent burn interval, greater than 10 years, since this design would specify a small volume of storage (McCuen et al., 1990b). The risk of failure will decrease if burn intervals < 10 years are used and if the return period is increased. If a policy specifies the use of a particular return period, making the burn interval shorter can significantly reduce the risk of failure. For the Los

Angeles area the average burn interval is 10 years. If man-induced fires are a common problem, the policy might specify a shorter burn interval. In high hazard areas, the risk of failure can be minimized by selecting a debris flow return period of 50 or 100 years and a short burn interval of 2 years. In a low hazard area, debris flow return periods of 5 years or less and an average burn interval of about 10 years may be appropriate. In any case, the hazard level should influence the selection of these two important policy variables.

Debris flows can occur during one or more storm events over the rainy season. Therefore, the period during which debris is expected to accumulate in a basin during the course of a year should be based on the typical duration of the rainy season for the region and the frequency with which local agencies will be able to provide proper maintenance. For the Los Angeles area, the rainy season is 4–6 months long. The computed volume of storage for a debris basin should be based on this period (i.e., 0.3–0.5 years). A basin will be overdesigned if the computed seasonal volume from eqn. (1) is not corrected by multiplying by the length (as a fraction of a year) of the rainy season.

A debris basin must be maintained in order to prevent failure of the basin. The monitoring procedure described previously accounts for various hazard levels during the estimation of real-time sediment yields that result from various rainfall depths. Estimated volumes for high hazard areas should be greater than those for low hazard areas. Basin inspections in areas that require high or moderate hazard designs should be more frequent than for the low hazard areas since the estimation of the volume of accumulated sediment is based on a greater yield per storm. The more frequent inspections will help to ensure that sufficient capacity remains in the basin in the case of a major debris flow. The estimated debris should be multiplied by some factor if the watershed has recently burned to account for the larger volume. The seasonal debris volume increases by a factor of about 5 during the season following a fire (Johnson et al., 1990) although Wells (1981) has reported that the volume for a single debris flow may increase by up to 25 times. This seasonal factor will decrease with time as the watershed begins to recover. For the seasonal volume the factor may reduce to 2 for the second season following a fire.

Policies should also define the levels at which the basin should be dredged. The basin should be inspected following each rainy season (yearly) to determine whether or not the basin should be dredged. If the basin does not require dredging, the estimated accumulation should be adjusted to the actual volume of debris within the basin. A systematic failure to maintain a basin essentially increases the risk of failure.

CONCLUSIONS

To ensure the safety of life and property downstream from a debris basin, the basin must be properly designed and maintained. A design should be based on a volume of storage to contain the seasonal debris flow. Proper maintenance will minimize the risk of failure of the basin.

To establish policies that set design standards and maintenance requirements for debris basins, it is first necessary to determine the potential hazard to the community downstream from the basin. Once a hazard level has been established, a debris return period and burn interval, which are the two most important design variables, must be selected for the design of basins. For low hazard areas the return period may be shorter (i.e. 2–5 years) and the burn interval longer (i.e. 10–25 years) than for moderate and high hazard sites, where a return period of 50–100 years and a burn interval of 2–5 years might be used. A basin located in an area where the hazard is considered low will require a relatively small capacity.

As the area below a debris basin undergoes land development, the hazard level may change, either gradually or abruptly. Areas beneath existing basins may be classified as high, moderate, or low hazard areas and the appropriate basin size computed. If the capacity of an existing basin that has been designed on the basis of a low hazard level is less than that needed for a new hazard level, then the storage volume of the basin should be increased. If an existing basin is situated in a low hazard area and the capacity is sufficient for that area, then land use planning should ensure that this area will remain low hazard by retaining an open space type of land zoning that restricts the building of new roads and buildings; otherwise the basin will have to be modified according to the adjusted level of hazard. Furthermore, it is reasonable to consider future hazard levels in the design of a debris basin to minimize the need for retrofitting modifications.

It is possible that in certain areas the designed volume of storage of the debris basin may be too large for constructing the basin in that particular location. In this case the designer may wish to consider multiple basins where, instead of constructing one large basin at the mouth of the main canyon, several smaller basins could be constructed at the mouths of tributary canyons. Other alternatives to constructing one large basin are those that reduce the amount of debris delivered to the debris basin such as: (1) dividing the watershed into a number of subwatersheds and constructing a series of basins at the subwatershed outlets; (2) constructing 'check' dams at several locations up-canyon to reduce the volume and flow rate of the debris flow before it reaches the catchment basin; (3) installing debris fences or slit dams that retard the flow of the debris en route to the catchment basin; (4) stabilizing areas that are subject to debris failures.

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