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Journal of Hydrology 244 (2001) 181–200

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Using the sediment record in a western Oregon flood-control reservoir to assess the influence of storm history and logging on sediment yield

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Received 25 February 2000; revised 30 November 2000; accepted 26 January 2001

Abstract

Dorena Lake, a flood-control reservoir with a 686 km^2 watershed in the western Cascade Mountains of Oregon, contains a 50-year record of sediment deposition. By measuring the amount of lake sediment, performing ^{137}Cs dating, and examining the stratigraphy of sediment cores, information was obtained about variations in the sediment yield of the watershed. The average yield for 50 years is 108 tons/km^2/year, and rates for shorter time periods vary from 42 to 269 tons/km^2/year depending on the time of average and the occurrence of large storm events. A comparison of sediment yield values with timber harvesting rates and with the number of high-discharge days during different time periods implies that sediment yield is controlled primarily by flood magnitude and frequency. The amplitude of variation in yield that might be produced by changes in logging rates or methods is too small to be detected with the methods used in this study because in large watersheds (1) the effects of localized events tend to be averaged out and (2) sediment delivery ratios are generally low. Also, the reservoir was constructed after a significant portion of the watershed had been logged, so the data cannot be compared with pre-disturbance sediment yields. This study shows that reservoirs in the Western Cascades are worthy of further study; but information is needed to constrain reservoir trap efficiency, and problems of scale in large watersheds may hinder the detection of land-use influences on sedimentation.

Keywords: Sediment yield; Reservoir; Oregon; Logging; Land use

1. Introduction

Along with concern about declining salmon populations, the impact of logging on the environment is one of the most prominent and contentious issues in the Pacific Northwest region of the United States today. Many concerns about logging activities are related to their effects on erosion (Sidle et al., 1985). A number of studies performed in small, western Oregon watersheds have shown an increase in sediment production after clearcutting and road building (Mersereau and Dyrness, 1972; Beschta, 1978; Swanson et al., 1982; Grant and Wolff, 1991), primarily because the frequency of episodic mass movements tends to increase. Unpaved logging roads have also been shown to be significant sediment sources (Reid and Dunne, 1984; Reid, 1998). Landslides and higher suspended sediment concentrations can lead to degraded aquatic habitats and water quality, so logging activities have the potential to create problems for humans and salmon alike.

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PII: S0022-1694(01)00331-6

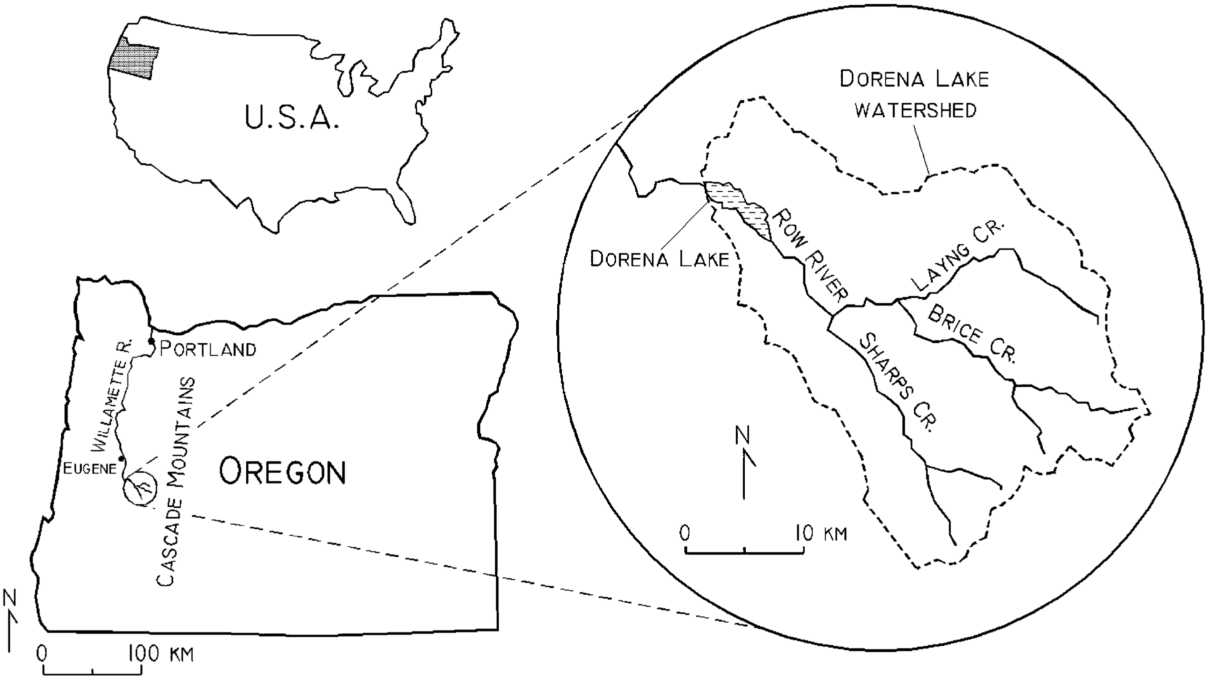

Fig. 1. Map showing the location of the Dorena Lake watershed within the state of Oregon. In the watershed, Dorena Lake, the Row River, and the major tributary streams are also shown.

The effects of logging on first- and second-order watersheds are well documented, but proper management of soil and water resources in large drainage basins requires information about the cumulative effects of land use at large spatial and temporal scales. For example, it has been suggested that localized erosion problems may have a negligible impact on sediment yield and water quality when averaged over the area of larger watersheds (Sullivan, 1985). Long-term erosion and water quality monitoring data from large watersheds are needed to address these issues, but such monitoring is expensive and difficult. One solution to this problem is to examine the sedimentary record contained in a lake or reservoir at the mouth of a large watershed to gain an understanding of how sediment yield has varied over time.

In western Oregon, flood-control reservoirs managed by the U.S. Army Corps of Engineers (USACE) are located on most of the major tributaries of the Willamette River that flow out of the Cascade Mountains. Although some of these reservoirs were constructed as early as the 1940's, they have not been extensively studied and therefore represent an untapped information resource for sediment-related environmental problems in this region. One of the factors that have deterred scientific study is the complex management style of the reservoirs that involves significant changes in lake levels on a seasonal and storm-by-storm basis. The resulting transgressions and regressions of the shoreline can produce complex sedimentation patterns on the lake-bottoms. Partial draining of reservoirs after winter floods is thought to allow much of the suspended sediment to pass through the dams (H. Henderly, USACE Park Manager, personal communication, 1998), possibly compromising the quality of the sedimentary record that is retained. This study investigates the extent to which these potential problems can be overcome to obtain useful information about sediment yield and sedimentation rates for a large watershed.

To address these issues, Dorena Lake, a reservoir with a 686 km^2 watershed in the southern part of the Willamette Basin, was studied in detail. By performing a sedimentation survey, dating sediment cores

Table 1
Dorena Lake watershed land ownership and harvest history (area in km^2)

Subwatershed	USFS	BLM	USACE	Private	Total area	% harvested by 1996
Layng Cr.	149.8	0.0	0.0	20.8	170.6	62%
Brice Cr.	129.7	0.0	0.0	17.3	147.0	38%
Sharps Cr.	71.8	36.5	0.0	63.7	172.0	51%
Row R.	0.0	41.1	8.8	146.3	196.3	97%
Total	351.4	77.7	8.8	248.1	686.0	64%

with ^{137}Cs, and correlating core stratigraphy using hydrologic records, information was obtained about reservoir sedimentation dynamics over a 50-year period. The influence of flood events and logging activities on sediment yield was then investigated.

2. Study area

2.1. Dorena Lake watershed

The Dorena Lake watershed (686 km^2) is located in the western Cascade Mountains of Oregon (Fig. 1). Elevation within the watershed ranges from 235 m near the dam to 1826 m on the southeastern rim of the watershed, and the average slope is 38% (range = 2–70%). The climate is temperate, and the watershed receives an average 1300–1800 mm of rainfall per year. The primary vegetation is Douglas fir, western hemlock, and western red cedar forests with small remnants of oak savannah in the Dorena Lake valley. Settlement by Euro-Americans began during the 1850's, but there are currently fewer than 600 residences in the watershed, mostly concentrated in three small communities in the Row River valley. Commercial lumbering began in the 1880's with the construction of the watershed's first sawmill. Major timber harvesting did not occur until a railroad line was constructed in the watershed around the beginning of the twentieth century. The dominant land use continues to be forestry, and 64% of the basin has been cut, some of it more than once (Table 1; USDI Bureau of Land Management, 1995; USDA Forest Service, 1995; USDA Forest Service, 1997; USDA Forest Service and USDI Bureau of Land Management, 1999). The eastern half of the watershed is part of the Umpqua National Forest and is managed by the U.S. Forest Service (USFS). In the western half of the watershed, the Bureau of Land Management (BLM) manages patches of land interspersed with privately owned tracts. USACE manages Dorena Lake and some surrounding lands (Table 1).

The bedrock in the Dorena Lake watershed ranges in age from 17 to 45 Ma (Sherrod and Smith, 1989) and is predominantly volcanic in origin. Volcanic deposits include lava flows, lahars, pyroclastic flows, tuffs, and volcaniclastic mudstones and sandstones. Soils in the watershed are mostly Inceptisols with some Ultisols (USDA Soil Conservation Service, 1987). Colluvial soils on steep slopes and soils developed on lava flows tend to be shallow, stony, and fairly stable. Pyroclastic deposits, mainly tuffs and breccias, produce soils that are deeply weathered and rich in expandable clays and amorphous materials, making them susceptible to deep-seated, slow-moving landslides (Youngberg et al., 1975; Taskey et al., 1979). Earthflow terrains are located throughout much of the watershed and can be chronic sediment sources. Debris slides and debris flows occur occasionally, usually during very intense rain-on-snow events (Harr, 1981), and are a major source of sediment despite their relative infrequency.

2.2. Dorena Lake

Dorena Lake was completed in 1949 by USACE as part of the Willamette Basin flood-control project. It regulates the Row River, a tributary of the Coast Fork of the Willamette River, and is located 10 km east of the town of Cottage Grove, Oregon. The dam is a 1-km-long earthfill structure with a concrete spillway section containing five outflow conduits (gates) located near the base of the spillway at an elevation of 225 m. Lake level and outflow discharge are regulated by letting water out of one or more of the gates, and no

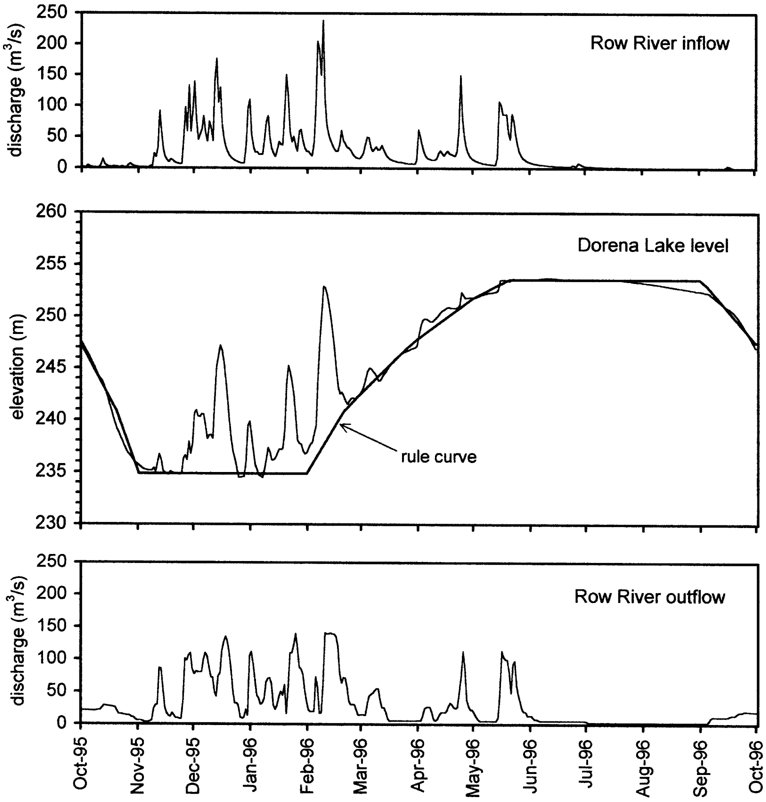

Fig. 2. Average daily Row River inflow and outflow discharge and Dorena Lake elevation during water year 1996. Inflow peaks generally correspond with peaks in lake level, resulting in a broadening and sometimes truncation of outflow peaks. USACE tries to match the rule curve elevations for the lake unless flood control during the rainy season or flow augmentation during the dry season requires it to do otherwise.

scour valve was constructed to allow sediment to be flushed from the reservoir. At full pool (spillway elevation = 254.5 m), the lake originally had a capacity of 95.6 million m^3 and a surface area of 7.4 km^2 (US Army Corps of Engineers, 1953). A picture of the reservoir and some additional information are available from USACE at http://www.nwp.usace.army.mil/OP/V/WVPRJTS.HTM#Dor.

Management of Dorena Lake follows an annual cycle designed to maximize flood control during the rainy season (mid-October to mid-May). Water is also conserved during the summer dry season for recreation on the lake and for pollution dilution and irrigation withdrawals on the Willamette River (Fig. 2). The lake level is kept at summer high-pool elevation (253.6 m) from late May to early September. Drawdown then begins so that winter low-pool elevation (234.8 m) is reached by the end of October. From February to May, the lake is slowly filled to its summer high-pool elevation. At low pool, lake volume is only 10% of that at full pool, so most of the lake basin capacity is available to hold floodwaters. When a storm occurs, water is held in the reservoir to keep outflow below a certain discharge (usually 142 m^3/s; Fig. 2), and the lake fills partially or completely, depending on the size of the runoff event. After the storm, water is drained out over a period of days or weeks to reach the desired lake level. As a result of these management practices, the lake bottom experiences annual and, during the rainy season, storm-related transgression–regression events that last one or more weeks. Sediment influx to the lake has been observed to occur mainly during flood events and is especially high after the occurrence of mass movements in the watershed. During

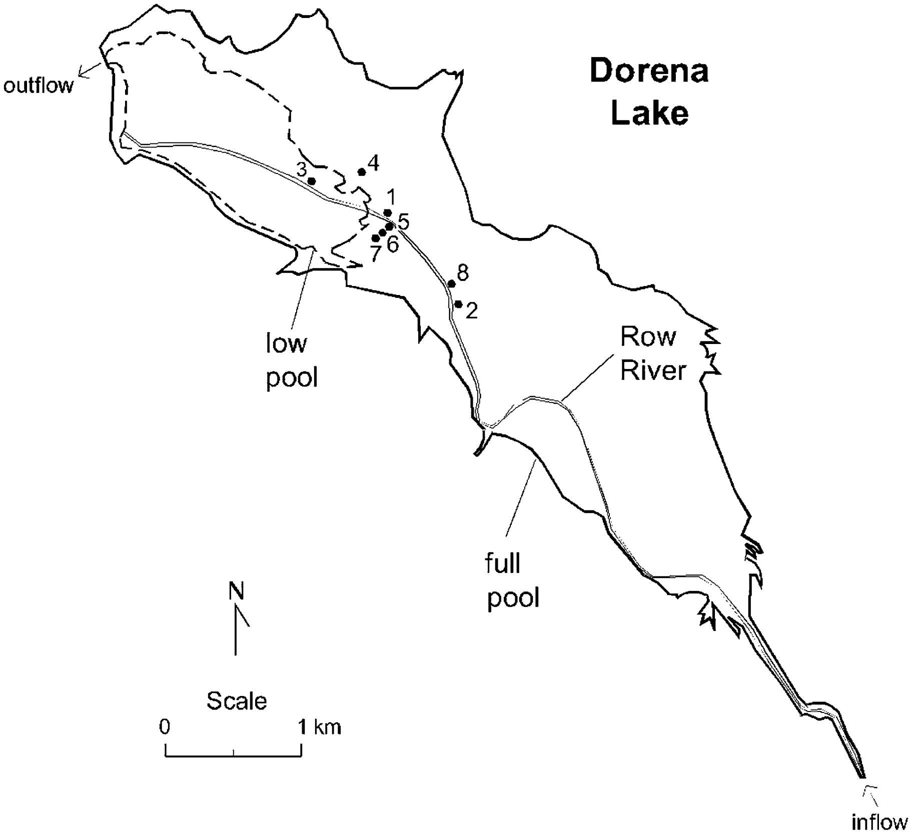

Fig. 3. Map showing the location of sediment cores (1–8) taken from Dorena Lake for measurement of stratigraphy, particle-size analyses, and ^{137}Cs dating. The outlines of the lake at full-pool and low-pool elevations and the Row River channel are also shown. Other tributaries (not shown) enter the lake directly, but these contribute <20% of the inflow to the lake.

quiescent periods, the cobble-bedded and bedrock-controlled streams feeding the lake have very low turbidity.

3. Methods

3.1. Sediment cores, ^{137}Cs dating, and sedimentation survey

Eight sediment cores (0.62–1.8 m long) collected from Dorena Lake were subjected to detailed study (Fig. 3). Each core represents the complete thickness of lake sediment at its sampling location, as determined by the presence of either pre-lake soil or an impenetrable cobble layer at the base of the core. The cores were taken back to the lab virtually intact, and their stratigraphy was described in detail. The base of deposits from flood events in December 1955, December 1964, January 1971, December 1981, February 1986, and November 1996 were used for correlation from core to core. These events were chosen for correlation because they were all of large magnitude, spaced at intervals of 4–11 years, and characterized by fairly distinctive deposits, usually a thick basal sand grading upwards into silt and clay. The exact choice of layer for a particular storm is somewhat subjective, but similarities between cores and comparison with hydrologic records aided in correlation.

Core 3 was split into fifteen 2–5 cm long sections along natural breaks, and duplicates of cores 1 and 2 were each cut into fifteen 6.6 cm long sections, all of which were allowed to air dry. Particle-size analyses

Table 2
Dorena Lake sediment properties

Density	0.79 ± 0.08 tons/m^3
LOI	5.2 ± 2.3%
Volume	3,000,000 ± 100,000 m^3
Total mass	2,400,000 tons
Inorganic mass	2,300,000 tons
Average thickness	0.46 m

were performed on these samples using the hydrometer method described by Gee and Bauder (1986). The samples from cores 1 and 2 were also analyzed for ^{137}Cs at the USDA ARS Hydrology Laboratory in Beltsville, Maryland. Gamma-ray analyses were made using the CANBERRA GENIE-2000 Spectroscopy System, a software/hardware package set up to receive input into two 8192 channel systems from two solid state crystals: a Canberra Lithium-drifted Germanium crystal (Geli — 15% efficiency) and a Canberra High purity coaxial Germanium crystal (HpC — 30% efficiency). The system was calibrated and efficiency determined using an Analytic mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. Estimates of radionuclide concentration of the sediment samples were made using CANBERRA GENIE-2000 software. ^{137}Cs was detected at 662 keV and count time for each sample was 30,000 s, providing a measurement precision of ±4–6% on most samples. Comparisons of the same sample counted on both detectors found no significant differences in estimated ^{137}Cs content.

Another forty sediment cores (0.19–1.11 m in length) were collected from a variety of locations across the lake bottom to determine the average density and organic matter content of the lake sediment. The volume and dry mass of these cores were measured. Small (3–5 g) splits of the samples were dried at 110°C, re-weighed, and then heated to 450°C. Water loss at 110°C was used to correct the sediment mass used in density calculations. Organic matter content of the lake sediment was determined from the loss on ignition (LOI) at 450°C. The reported average LOI value (Table 2) is corrected to reflect the fact that approximately 3% of the weight loss at 450°C was due to dehydroxylation of poorly crystallized clay minerals rather than burning of organic matter, as determined by LOI measurements made on pure clay samples from area bedrock. Autochthonous inorganic sediment components, such as precipitated carbonate minerals or siliceous diatom tests, were determined by microscopy to be only trace constituents of the sediment.

To determine the total amount of sediment deposited in Dorena Lake, a lake sedimentation survey was performed. When the reservoir was at low pool, the total lake-sediment thickness on the exposed lake bottom was measured with a coring device on foot on an approximately 75 m grid. On the low pool itself, a ‘spud’ was used from a boat with a grid spacing of approximately 120 m (Rausch and Heinemann, 1984; Ritchie and McHenry, 1985). At each of the 885 measurement points, location was obtained using a global positioning system with a differential beacon receiver (position error = 5 m or 0.001% of the total lake bottom area). Additional constraints on the sediment thickness in the main delta area were obtained using an original topographic cross-section surveyed by USACE just after the reservoir was completed. The data were used to create an isopach map of sediment thickness and to calculate the total volume of lake sediment. The total mass of inorganic sediment was obtained using the measured average sediment density and organic content described above. Thickness data from the sediment apron observed at the base of steep slopes around the edge of portions of the lake-bottom were not used in creation of the isopach map. In this way, material locally eroded and redeposited along shorelines was excluded from the sediment volume, mass, and yield calculations.

3.2. Land use history

Information about the logging history of the watershed was obtained from several sources. Clearcuts on aerial photographs from 1955 and 1964 were digitized to measure the areas harvested early in the life of the reservoir. Harvest and stand age data for 1972–1995 were provided by the Laboratory for Applications of Remote Sensing in Ecology at the Forestry Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service, in Corvallis, Oregon. This information was obtained from six different years of Landsat images (Cohen et al., 1998). The USFS also provided geographic information system (GIS) coverages for timber

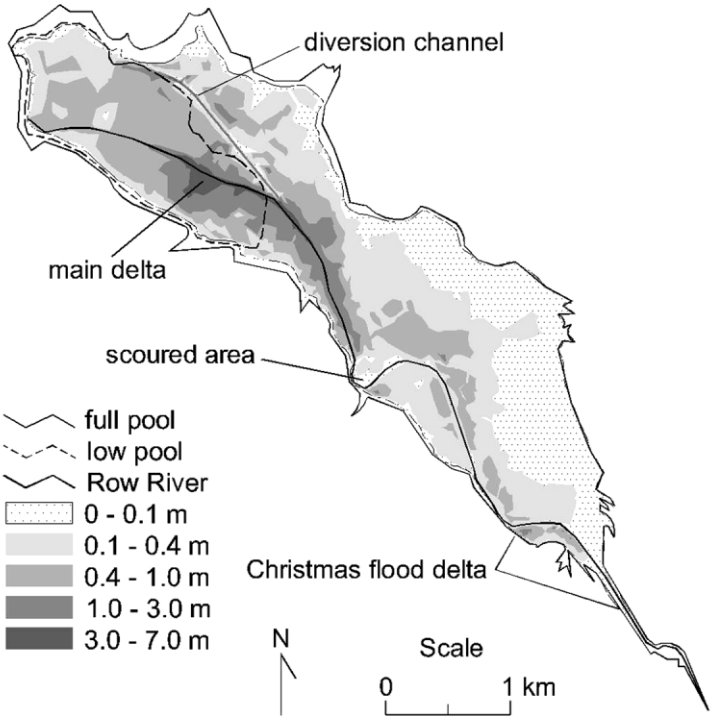

Fig. 4. Map of lake sediment thickness. Deposits are thickest along the banks of the Row River and in its main, low-pool delta. The temporary delta formed by the Christmas flood of 1964 is also evident, as is a small area on the inside of a meander bend which is often scoured during large storms. The linear feature running northwest along the low-pool boundary is a diversion channel dug by USACE during dam construction. It was used to temporarily divert flow from the Row River through the outflow conduits in the spillway so that the earthfill portion of dam could be completed. Like the original river channel below low pool, it contains a thick mantle of sediment.

harvesting in the eastern half of the watershed. Insufficient data were available to reconstruct the growth of the road network throughout the entire watershed in a detailed way, but the online database maintained by the Oregon State Service Center for Geographic Information Systems provided a GIS coverage for roads present in 1995. Some generalizations could also be made from the aerial photographs and satellite images.

4. Results

4.1. Sediment yield

The sedimentation survey data yielded an isopach map of lake sediment thickness (Fig. 4). The map shows that much of the lake sediment resides in the delta that has formed where the Row River meets the winter low pool. Thick sediment deposits also occur along the river banks (natural levees) and in a river diversion channel and various broad, shallow pits dug into the valley bottom by USACE during dam construction. On the northeast side of the upstream portion of the lake, minimal sediment deposition has occurred. This area is shallow and flat, and it is inundated with sediment-laden water only during the largest winter flood events. At the upstream end of the lake, thick sediment deposits represent a temporary delta that formed when the lake overflowed during the huge 'Christmas flood' of 1964 (>100-year recurrence interval; Fig. 4). This flood and the distinctive deposits it produced are described in more detail in Section 4.3.

Except for the portions of the lake margin where steep hillslopes have been carved by wave action (which, along with the sediment apron formed at the base of these slopes, were excluded from the isopach map and sediment volume calculations), only one area of the lake bottom exhibits obvious signs of erosion. Scour occurs on the inside of a tight bend in the river where high-velocity flood waters bypass the meander and cross the lake bottom itself during overbank events (Fig. 4). On other parts of the exposed lake bottom, spring-fed streamlets appear to have just enough energy to keep their channels clear of the lake sediment deposited during the most recent innundation. Deposition occurs around these small channels, but there is no evidence of channel migration, although slumping of bank material occurs at some locations. In one instance, after a flood event partially filled the reservoir, ripple marks were observed on a large part of the lake bottom, but these appeared to be primarily depositional features. Raindrop imprints have also been observed, but the rapid development of a film of cyanobacteria, algae, liverwort, and fungi on the mud exposed during drawdown seems to help stabilize the sediment. Signs of erosional unconformities are lacking, so significant reworking of lake-bottom sediment does not appear to occur.

Dorena Lake contains 3.0 million m^3 of sediment which, if spread evenly over the depositional area of the lake bottom (6.6 km^2), would give an average thickness of 0.46 m (Table 2). After 50 years of operation, the reservoir has only lost 3% of its original capacity. The total mass of sediment is 2.45 million metric tons, of which 2.3 million tons is inorganic material. Assuming that the lake trapped all the sediment that entered it, the watershed has yielded a minimum of 66 tons/km^2/year of inorganic sediment for 50 years.

To calculate the actual watershed sediment yield, the trap efficiency (the percentage of sediment input that is retained in the lake) must be estimated. Using data from over 40 U.S. reservoirs, Brune (1953) determined that the average trap efficiency for normally ponded reservoirs could be closely estimated using the ratio of lake capacity to the average annual inflow of water (*C*/*I* ratio). The resulting curves are the most frequently used trap efficiency estimate for reservoir and lake studies, although they tend to underestimate the percentage of coarse sediment retained and overestimate the percentage of fines (Heinemann, 1984). This kind of average annual relationship is unlikely to be highly accurate for Willamette Basin flood-control reservoirs, however, because their lake capacities change through the year in an only partially predictable way. USACE attempts to follow its rule curves for lake levels, but a single storm event can take a lake from 10 to 100% of full-pool capacity and back again in a matter of days (Fig. 2). Of the sediment input to the lake during the event, almost all of the coarser material (sand and coarse silt) is deposited on the lake bottom, but some percentage of the fines (fine silt and clay) remains suspended long enough to pass through the dam and continue downstream. As lake capacity increases, so does the residence time of water and the amount of sediment that settles from suspension. Trap efficiency thus varies in a complex way as a reservoir is filled and drained in response to a flood event (Heinemann, 1984).

As an example, in a moderate flood event observed by the author in late December 1998, inflow turbidity and discharge peaked a day before a marked increase was seen in outflow turbidity. As inflow volume increased, USACE reduced the outflow discharge in order to hold the floodwaters in the reservoir, so the outflow turbidity peak actually corresponded to a low point in outflow discharge. Turbidity of the outflow remained relatively high for four days after the inflow peak and then began to taper off. Lake level rose over 9 m in the two days after the inflow peak and took two weeks to return to low pool elevation. The particle size of suspended sediment input into Dorena Lake ranged from clay to sand at the peak of the flood, but the outflow appeared to contain only clay and perhaps some fine silt. The complexity of this one event points to the difficulty in determining trap efficiency given the dearth of data on the behavior of Willamette Basin reservoirs.

Some attempt must be made to estimate the trap efficiency of Dorena Lake given the information at hand, however. A rough estimate may be obtained by applying Brune's empirical relationship, but it is necessary to choose a representative lake capacity. Because sediment influx to the lake occurs almost entirely during flood events in the wet season, it is reasonable to use the average lake capacity during that time (mid-October to mid-May). In this case, the *C*/*I* ratio is 0.040, and the trap efficiency is 75 and 62% on Brune's median and bottom envelope curves, respectively (Brune, 1953). Given USACE's tendency to release most or all of the reservoir's flood water (and the suspended sediment load it carries) in

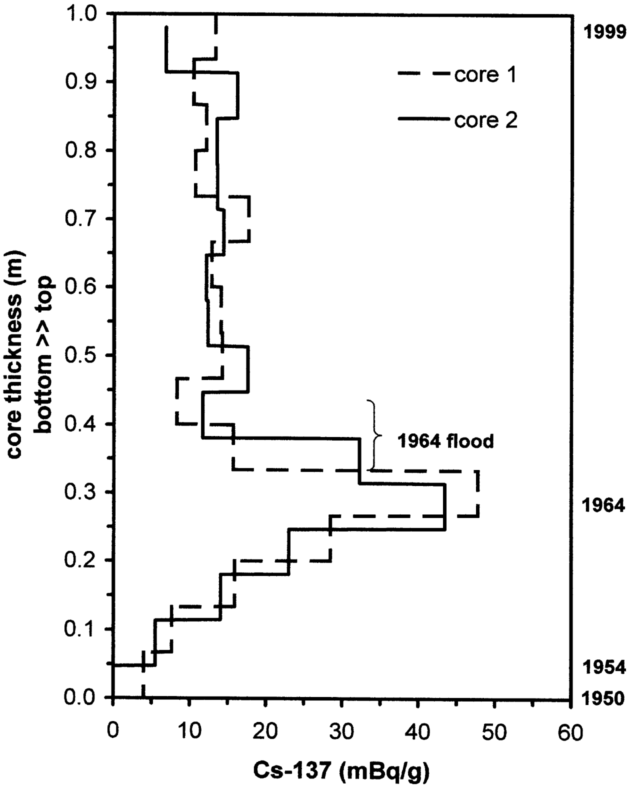

Fig. 5. ^{137}Cs results for samples from cores 1 and 2. The dates (water years) for various horizons of core 2 are shown on the right-hand side of the diagram, and the samples containing deposits from the Christmas flood of December 1964 are labeled.

the days and weeks after a flood event, the more conservative estimate of trap efficiency is likely to be closer to the actual value. With a trap efficiency of 62%, the average inorganic sediment yield of the watershed is 108 tons/km^2/year. The error in this value is likely to be large (perhaps ± 10–20 tons/km^2/year) because of the uncertainty involved; but using a single, average trap efficiency makes all the sediment yield values presented in this study internally consistent. If reliable data on trap efficiency eventually become available, these numbers can easily be recalculated.

4.2. ^{137}Cs dating

^{137}Cs is a radioactive isotope produced by nuclear bomb testing and nuclear power generation that is used fairly routinely for dating recent lake sediment (Wise, 1980). Prior to 1954, ^{137}Cs deposition from nuclear fallout was nonexistent or insignificant. Its presence in the atmosphere increased from 1954 to 1963–1964, reflecting an increase in aboveground nuclear tests. After the Test Ban Treaty of 1963 took effect, ^{137}Cs deposition began decreasing, and only a few, relatively localized events such as the Chernobyl accident have disturbed the trend. In sediment cores, the onset and peak concentration of ^{137}Cs are used to locate the 1954 and 1964 horizons, respectively (Ritchie and McHenry, 1990). Downward diffusion of ^{137}Cs may blur the location of the 1954 horizon, however (Wise, 1980; Ritchie and McHenry, 1990; Crusius and Anderson, 1995).

Since cesium adsorbs strongly onto clay mineral surfaces, it often resides primarily in the clay-sized fraction of sediment. As a result, ^{137}Cs content can sometimes be controlled more strongly by the particle-size distribution of a sample than by the age of the deposit, with an increase in the amount of sand-sized

Table 3
Sedimentation rates (cm/year) from ^{137}Cs dating

Water years	Core 1 (100 cm long)	Core 2 (98 cm long)
1965–1999	2.0	2.0
1954–1964	2.7	2.1
1950–1953	0	1.2

particles causing an apparent decrease in the ^{137}Cs concentration, for example (Ritchie and McHenry, 1990). To investigate this possibility in the Dorena Lake cores, ^{137}Cs content was plotted individually against the percentage of sand, silt, and clay in the samples, and linear regressions were performed. The plots show that clay and silt are positively correlated with ^{137}Cs and sand is negatively correlated, but the correlations are weak ($r^2 = 0.07 - 0.12$), indicating that particle size in this case is not a serious complication to dating.

Fig. 5 shows the results of the ^{137}Cs analyses from cores 1 and 2. The sample at the base of core 2 contains no ^{137}Cs, so it represents deposition during water years 1950–1953, the first years of reservoir operation. The base of the bottom sample of core 1 should be considered to represent 1954 because this sample contains a significant amount (>2 m Bq/g) of ^{137}Cs (J. Ritchie, personal communication, 1999), although some downward diffusion may have occurred. Peak ^{137}Cs values are found in the fifth sample up from the base of each core, so the middle of these samples represents water year 1964 (at approximately 30% total thickness). The tops of the cores were deposited in early 1999 just before sampling was performed.

The two samples in each core just above the 1964 layer contain less ^{137}Cs than the peak values. They have been determined by stratigraphic analysis to contain deposits from the Christmas flood that occurred early in water year 1965 (see Section 4.3). During this massive flood event, much of the sediment that reached the lake came from landslides that cut beneath ^{137}Cs-bearing surface horizons. The radionuclide signature of this flood deposit is therefore believed to have been diluted despite the fact that atmospheric deposition of ^{137}Cs remained high during this period of time.

Sedimentation rates for the two cores can be determined from the dated horizons (Table 3). There is some variation between the two cores, but rates are lowest during the first few years of reservoir operation (0 and 1.2 cm/year) and highest from 1954 to 1964 (2.1 and 2.7 cm/year). Downward diffusion of ^{137}Cs may be partially responsible for this apparent difference in rate. The last 35 years of reservoir operation had an intermediate sedimentation rate of 2.0 cm/year. The thicknesses of the two dated cores are a little more than twice the average thickness of lake sediment (1.0 and 0.98 m versus 0.46 m), so sedimenta-

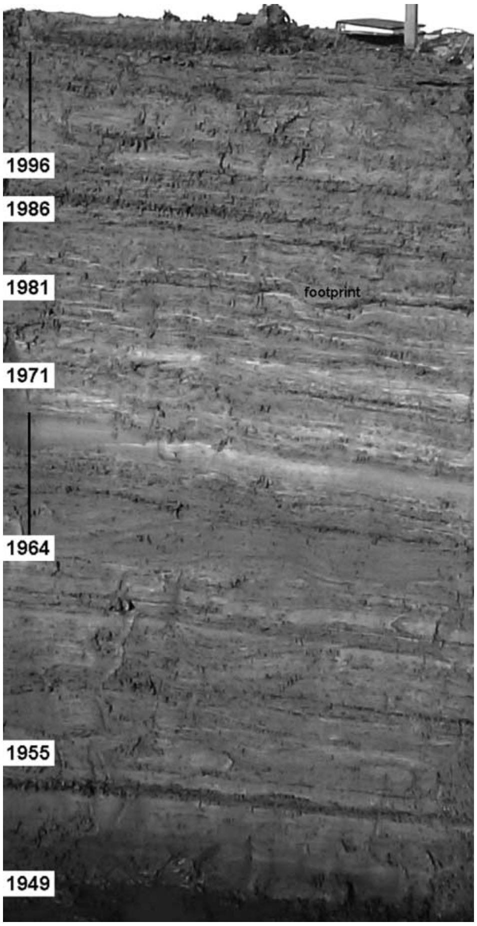

Fig. 6. Photograph of lake sediment in a trench on the lake bottom at the location of core 8, showing the laminated nature of the sediment. The section is 1.5 m thick. The base of each flood event used to correlate the cores is labeled with the calendar year of its deposition, and bars indicate the thickness of the 1964 Christmas flood and a package of several floods that occurred during 1996–97 rainy season (100- and 2–4-year floods).

Table 4
Stratigraphy and sedimentation rates for eight cores

Layer thickness (cm):

Time period	1	2	3	4	5	6	7	8
[a]11/96 to top	10.4	14.2	6.0	22.9	19.6	8.6	19.0	31.8
2/86 to 11/96	8.1	6.1	5.0	15.9	10.2	5.8	17.1	7.6
12/81 to 2/86	7.6	8.1	6.9	23.8	11.8	8.1	18.8	14.6
1/71 to 12/81	21.4	20.3	9.9	34.5	29.1	12.1	40.8	15.9
[a]12/64 to 1/71	15.6	10.2	8.9	19.4	20.9	15.3	23.5	27.9
12/55 to 12/64	13.7	16.4	11.5	26.3	20.9	8.0	38.2	35.6
10/49 to 12/55	10.4	11.0	4.4	19.5	15.9	10.0	22.1	19.1
Total	87.2	86.3	52.6	162.3	128.4	67.9	179.8	152.4

Sedimentation rate by layer (% of core deposited per year):

Time period	1	2	3	4	5	6	7	8	Average
[a]11/96 to top	5.6	7.7	5.2	12.9	15.9	13.2	11.0	6.8	9.8 ± 3.8
2/86 to 11/96	0.9	0.7	0.9	0.9	0.7	0.8	0.9	0.5	0.8 ± 0.1
12/81 to 2/86	2.1	2.2	3.1	3.5	2.2	2.8	2.5	2.3	2.6 ± 0.5
1/71 to 12/81	2.3	2.2	1.7	2.0	2.1	1.6	2.1	1.0	1.9 ± 0.4
[a]12/64 to 1/71	2.9	1.9	2.8	2.0	2.7	3.7	2.2	3.0	2.7 ± 0.6
12/55 to 12/64	1.7	2.1	2.4	1.8	1.8	1.3	2.4	2.6	2.0 ± 0.4
10/49 to 12/55	1.9	2.0	1.3	1.9	2.0	2.4	2.0	2.0	1.9 ± 0.3

[a] Time period contains a ≥100-year flood.

tion rates for the lake, as a whole would range from 0.55 to 1.24 cm/year.

4.3. Sediment stratigraphy

Particle size analyses of samples from cores 1, 2, and 3 reveal that the majority of the sediment in these cores is silt, with lesser amounts of sand and clay. Samples average 54% silt, 28% sand, and 18% clay, and most plot in the silt loam field of the U.S. Department of Agriculture soil textural classification triangle (Soil Survey Staff, 1975). Coarser, sand- to granule-sized sediment has been observed in the Row River delta, and finer sediment can be found in individual laminations.

In general, Dorena Lake sediment deposits above low pool are composed of sand-clay couplets punctuated by a few layers of organic material (Fig. 6). The couplets are paired laminations, usually clayey sand overlain by sandy or silty clay, that represent single flood events. The texture and thickness of the couplets vary with the magnitude and duration of the event. Similar event-generated couplets have been observed in lakes and reservoirs around the world (Wood, 1947; Murray-Rust, 1972; Christiansson, 1979; Lambert and Hsu, 1979; Laronne, 1987) and are usually attributed to deposition from turbidity currents of various sorts (underflows, interflows, or surface flows depending on the densities of current and lake water). The total number of couplets in the lake sediment increases with proximity to the low pool and the Row River because areas closest to the low pool and the river experience fairly frequent inundation and deposition from floodwaters. Farther up the lake, couplets are fewer in number and represent only events large enough to substantially fill the reservoir. Within the low pool area, sediment is fairly homogeneous in texture, few distinctive layers are present, and the laminations that are present are usually only a few millimeters thick.

The Christmas flood of December 1964 produced a thick, distinctive deposit that is identifiable across much of the lake bottom that is exposed during the winter (Fig. 6). The base of the unit is a medium sand, >2 cm thick and sometimes oxidized to an orange color. This sand grades upward into a laminated sandy clay several centimeters thick that has both dark blueish gray and brownish gray layers. The sandy clay grades into a light gray clay layer that is only a few millimeters thick in most places. Near the upstream end of the lake, this layer is overlain by <2 cm of silty clay that forms the top of the flood

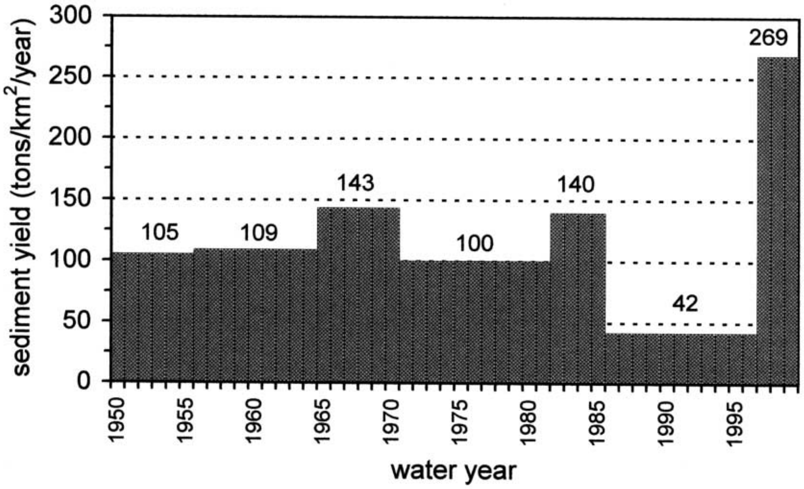

Fig. 7. Variation in measured sediment yield (tons/km^2/year) over the 50-year record for Dorena Lake. The high yield for the 1997–1999 time period is based on the average sedimentation rate obtained from cores taken during both water years 1998 and 1999. This value is high probably because of the impact of a large flood on sediment yield averaged over a short period of time and possibly because the top layers of the cores are less compacted than the lower horizons.

deposit. In areas closer to the low pool, however, the gray clay is overlain by several centimeters of sand or sandy clay.

The events of the 1964 flood appear to correlate closely with certain features of the deposits left behind. On December 21, 1964, discharge on the Row River began to climb sharply in response to heavy rains and rapid snowmelt. It peaked at 937 m^3/s on December 22 (for comparison, the mean annual flood is 347 m^3/s), by which time Dorena Lake had risen over 20 m from low pool to the point that water was pouring over the concrete spillway on the dam. Numerous landslides occurred in the watershed, mobilizing large quantities of sediment. The laminated, medium sand at the base of the flood deposit was probably laid down during the transgression period while water flowed over the surface of the lake bottom. A new, temporary delta began forming at the upstream end of the lake. Lake elevation peaked the next day at 2.75 m above the spillway, and lake volume reached 118 million m^3 of water. The uncontrolled outflow peaked at 487 m^3/s, more than three times the downstream channel capacity, and water continued to go over the spillway for seven days. During this high stand, the graded bed of sandy clay capped with light gray clay was probably deposited as suspended sediment settled out of the turbid lake waters. The lake was then drained back down to low pool elevation over the following 10 days, producing the overlying silty clay and sand. The regression appears to have remobilized some of the sediment that was originally deposited in the river channel where the temporary delta formed.

Sediment layer thicknesses and sedimentation rates for eight sediment cores are listed in Table 4. Core stratigraphy permitted identification of seven specific flood events, which were then correlated from core to core and used to divide the 50-year history of the reservoir into seven time periods. Because the length of the different cores varies from 52.6 to 179.8 cm depending on the coring location and depositional environment, sedimentation rates are expressed as the percentage of core length deposited per year. Direct comparison of sedimentation rates among cores is then possible, and average rates can be applied to the total volume of lake sediment to calculate the sediment yield of the watershed for different time periods (discussed below). Excluding the most recent time period (November 1996 to the top of the cores), average sedimentation rates for the eight cores range from 0.8 to 2.7%/year and are highest during water years 1965–1970 and 1982–1985 (Table 4). The lowest rate occurs from 1986 to 1996. Rates vary somewhat between cores, but their standard

Table 5
Harvest history for the Dorena Lake watershed

Water years	Harvested area (km^2)	Harvest rate (km^2/year)
1992–1995	21.8	5.5
1989–1991	15.4	5.1
1985–1988	31.2	7.8
1978–1984	37.1	5.3
1973–1977	21.9	4.4
1965–1972	47.3	5.9
1956–1964	62.5	6.9
1950–1955	27.8	4.6

deviation is low (0.1–0.6). Much of this variation is likely due to differences in the depositional environments of the cores.

The most recent time period has an extremely high average sedimentation rate and a high standard deviation between cores (9.8 ± 3.8%/year). The length of time used to calculate the rates was measured from the November 1996 event (a 100-year flood) to the dates of coring. This time period is so short that deposition rates are highly dependent on the time in which the cores were taken. Cores 4, 5, 6, and 7 were collected in late 1997 and have the highest rates; cores 1, 2, 3, and 8 were collected in 1999 and have much lower rates. If several more 'normal' years were included in the calculations, the rates would presumably approach those of previous time periods. As the Christmas flood in the 1965–1970 time period illustrates, the effect of a large flood on sedimentation rate is moderated when it is averaged with several less-eventful years. The deposits from the two ≥100-year floods (December 1964 and November 1996) together account for approximately 15% of total sediment thickness in the cores, however, so events of this magnitude clearly have a dramatic effect on sedimentation in Dorena Lake.

The sediment yield for the watershed during each of the seven time periods delineated in Table 4 can be calculated from the average sedimentation rates for the eight cores. The average rates are taken to represent a percentage of the total reservoir sediment volume deposited each year during a given time period. When this percentage is multiplied by the total volume of sediment (3.0 million m^3) and its average density (0.79 tons/m^3) and divided by both the average trap efficiency (0.62) and the watershed area (686 km^2), sediment yield is obtained (Fig. 7). For water years 1950–1996, rates vary between 42 and 143 tons/km^2/year among time periods. The yield for the most recent period (1997–1999) is obtained by subtracting the cumulative yield at the end of 1996 from the total yield and dividing the result by 3 years. This large value (269 tons/km^2/year) again shows the influence of a 100-year flood on a very short period of record. Because of compaction, the actual bulk density of sediment layers may also increase with depth, causing the sediment yield values from upper layers to be somewhat inflated. Measurements performed on the top and bottom halves of a few cores showed little difference in density, however, so compaction probably does not have a significant impact on the values presented here.

4.4. Timber harvesting and road building history

Table 5 shows how the amount of land subject to clearcut forest harvest has varied over the period between 1950 and 1995. Harvest rates are fairly constant, remaining between 4 and 8 km^2/year over the 46-year record. At least 15% of the watershed had been cut before the lake was constructed, and most of this logging occurred outside the Umpqua National Forest. Aerial photographs and satellite images show that private landowners clearcut the western half of the watershed more completely and in larger units than was done on national forest land. Rates of reforestation after clearcutting have increased over the past few decades as replanting or seeding conifer plantations became standard practice; but some areas, especially steep south-facing slopes, have proved difficult to reforest.

The road network on private lands in the western part of the watershed was already well established by the time the reservoir was completed, but early roads on Forest Service lands were primarily located in the Layng Creek drainage area. Roading throughout the watershed then paralleled cutting from the 1960's to 1980's. The total length of roads in the watershed in 1995 was approximately 975 km, with an average of 1.4 km of road per square km of drainage area both inside and outside the national forest boundary.

5. Discussion

According to a compilation of reservoir sedimentation data reported through 1975 (Dendy and

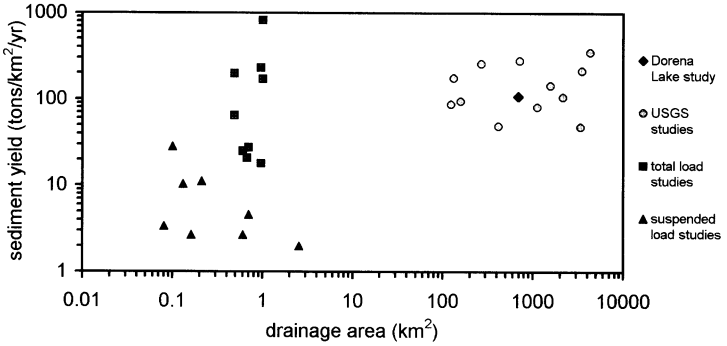

Fig. 8. Plot of drainage area versus measured average sediment yield for the Dorena Lake watershed and other watersheds in the region. U.S. Geological Survey (USGS) data were collected using depth-integrated sampling techniques on a daily basis in large watersheds in western Oregon (18-year records for Elk Creek, Steamboat Creek, South Umpqua River, North Umpqua River, and Olalla Creek and 1-year records for Bull Run River and Elliot Creek) and western Washington (3-year records for the Deschutes, Nisqually, Snoqualmie, and Skykomish Rivers, and a 5-year record for the Chehalis River). Suspended sediment and total load data were collected for small, treated and undisturbed watersheds in the H.J. Andrews, Coyote Creek, and Fox Creek studies over periods 6–30 years. Values are from Larson and Sidle (1980); Grant and Wolff (1991).

Champion, 1978), the volumetric sediment yield calculated from the amount of sediment measured in Dorena Lake over the 50-year record (87 $m^3/km^2/$year) is very close to the average value for Pacific Northwest reservoirs (80 $m^3/km^2/$year). This yield is low compared to other forested, mountainous areas in the United States, which average 131–367 $m^3/km^2/$year, and it is more than an order of magnitude less than the yield of the southeastern piedmont region (Renwick, 1996). Taking sediment density and estimated reservoir trap efficiency into account, the average sediment yield of the Dorena Lake watershed is approximately 108 tons/km^2/year. This value is low compared to the global average of 150 tons/km^2/year (Walling and Webb, 1983), but it is similar to yields measured in other large watersheds in western Oregon and western Washington (Fig. 8; Larson and Sidle, 1980).

Worldwide comparative studies show a tendency for sediment yield to decrease with increasing basin size, primarily because more opportunities for sediment storage exist within larger watersheds (Dendy and Bolton, 1976; Walling and Webb, 1983). Studies in the Pacific Northwest have shown little or no decrease in sediment yield with increasing drainage area (Renwick, 1996), however, and this pattern is not evident in Fig. 8. Small watersheds (<10 km^2) in this region have a wide range of sediment yield, and the magnitude of yield depends heavily on whether or not a large, landslide-producing storm event occurred during the period of measurement. Sediment transport by streams is supply-limited, and erosion rates tend to be quite low unless a mass movement occurs. For this reason, Grant and Wolff (1991) suggested that measurements of sediment yield in small, paired watershed studies have limited applicability in this type of landscape dominated by episodic mass-erosion events. Differences in the methodology (e.g. total versus suspended load) and timing between studies may also account for some of the variability (Fig. 8). In any case, large watersheds presumably provide a more consistent measure of yield because the effects of individual landslides are averaged over a much larger area. Temporal averaging is also important, however, because the effects of big floods are still clearly evident in watersheds as large as Dorena (Fig. 4). If the 1996 event is any indication, a measurement period of more than three years may be needed to generate a representative average sediment yield (Fig. 7).

For the Dorena Lake watershed, when the measured sediment yield for different time periods is plotted against the number of high-flow days per year on the Row River upstream of the lake (Fig. 9), hydrologic events appear to exert a strong control on sediment yield. The choices of discharge ranges shown (>150 and >285 m^3/s, corresponding to >1-year and >3-year floods) are somewhat arbitrary because

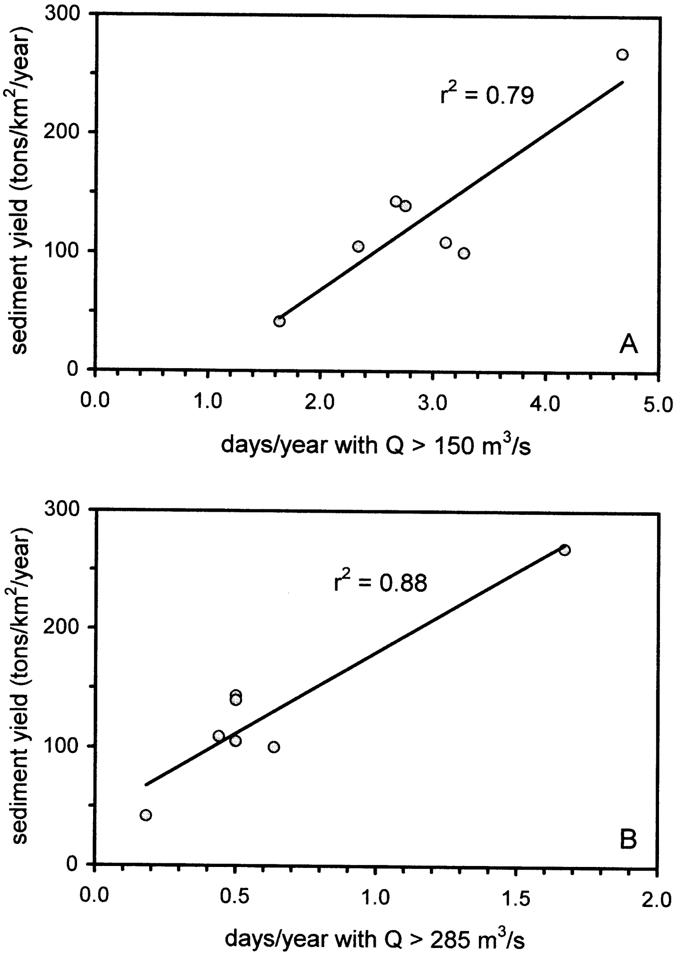

Fig. 9. Measured sediment yield for each of the seven time periods plotted against the number of days per year that the average daily discharge on the Row River above Dorena Lake is (A) above 150 m^3/s (>1-year flood) and (B) above 285 m^3/s (>3-year flood). The regression lines through the data points have positive slopes and high correlation coefficients, implying that sustained or repeated high-discharge flows during a given period of time result in a high sediment yield.

similar positive correlations and high r^2 values are seen over a wide span of discharges (up to >10-year floods). These plots illustrate that time periods, which contain larger numbers of high-discharge days tend to have increased sediment yield. The bulk of sediment transportation to the lake occurs during large floods, and the frequency and duration of high-flow events largely controls sediment yield for a particular time period.

Given the strong effects of floods and landslides on sediment production in the Western Cascades in general and in the Dorena Lake watershed in particular, how much effect does timber harvesting have? Small watershed studies indicate that the condition of a watershed (i.e. the amount, type, location, and age of vegetation, clearcuts, and roads) at the time of a storm event may strongly influence the amount of erosion that occurs (Grant and Wolff, 1991). Big events also push susceptible roads and hillslopes over the failure threshold, triggering mass movements. Once this threshold has been exceeded, the next large storm event may have fewer slide-prone sites to exploit and therefore result in fewer landslides and less sediment transport (F. Swanson,

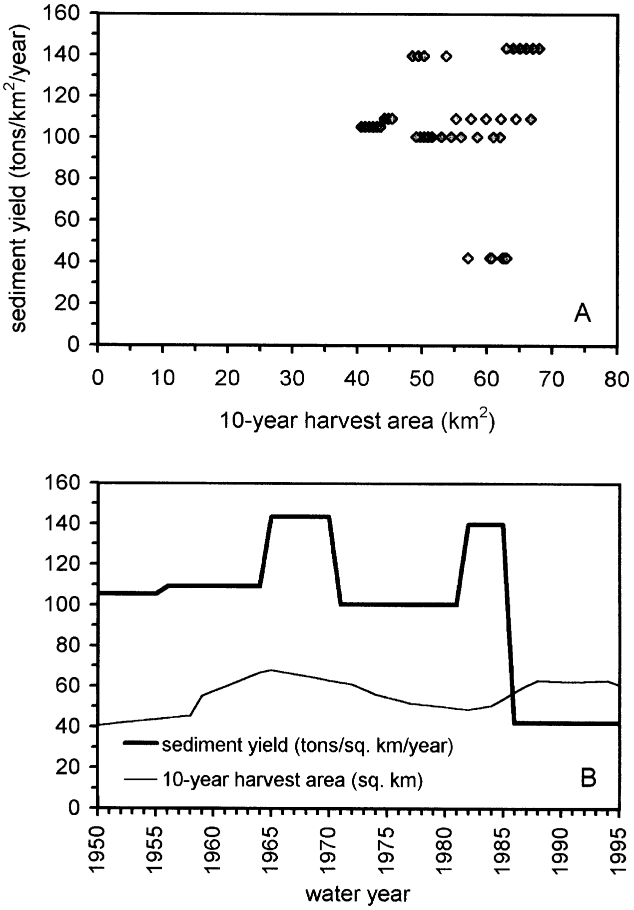

Fig. 10. (A) For each year from 1950 to 1995, the estimated area harvested during the previous 10 years (km^2) is plotted against measured sediment yield (tons/km^2/year). The harvest area is calculated as a 10-year running sum of the annual harvest rates listed in Table 5. Rates for the period from 1941 to 1949 were estimated to be 4.0 km^2/year. Because harvest rates and sediment yields were only available for fairly long blocks of time, the data points are arranged in rows. No obvious positive correlation exists between recently harvested area and sediment yield. (B) The same data set plotted chronologically, showing how harvesting and sediment yield varied over time. An increase in harvest rates during the late 1950's and early 1960's was followed a period of high sediment yield. The effects of the Christmas flood of 1964, which is largely responsible for the high yield in this period, may have been enhanced by the impact of relatively crude logging practices. During the 1980's and early 1990's, however, a high yield period occurred during a time of relatively low harvest rates, and increases in harvesting during the late 1980's and early 1990's correspond with a time of very low sediment yield. The November 1996 flood dramatically increased the sediment yield for the most recent time period, but no harvest data were available for 1996–1999.

personal communication, 1998). Logging may thus increase the effects of big storms, but the erosional response of a watershed to successive events may not be independent. Both the history and current condition of the landscape influence its reaction.

Basin size also has an effect on sediment yield, because in large watersheds there are increased sediment storage opportunities and a dilution of the localized effects of landslides. The decrease in sediment delivery ratio (the ratio of sediment yield at a basin outlet to sediment production within the basin) in larger watersheds works against the detection of relatively small or localized land use effects when only sediment yield is considered. In a large basin with spatially diverse land management practices, such as the Dorena Lake watershed, the sediment yield from relatively pristine areas may counterbalance more heavily impacted areas to give a fairly consistent average yield over time. As an example, a study on an 80 km^2 watershed on the Middle Santiam River in western Oregon showed that land-use-related slope failures that occurred during large storms only increased suspended sediment load temporarily (for a few days or weeks) and did not appear to increase average annual sediment yields (Sullivan, 1985).

In the Dorena Lake watershed, harvest rates vary comparatively little during the period of record (4.4–7.8 km^2/year; Table 5). A 10-year running sum of the harvest rates calculated for 1950–1995 can be generated to estimate the area of recently logged land, sparsely vegetated and fairly susceptible to erosion, that was present each year. When these annual values are plotted against sediment yield, no distinct correlation between the two variables is found (Fig. 10A). The data are not ideal because they are averages over blocks of time and not the actual yearly values; but no hint of a relationship is discernable. Plotting the data chronologically (Fig. 10B) shows that there could be a link between increases in logging prior to the Christmas flood of 1964 and increased sediment yield during the late 1960's. Perhaps the relatively crude logging practices used during the decades leading up to the flood enhanced erosion during the event by increasing the number of landslides that occurred, as was observed elsewhere in the Western Cascades (Grant and Wolff, 1991). This relationship does not repeat itself during the 1980's and early 1990's, however, when a period of high sediment yield precedes increased logging rates.

Although harvest rates have not changed markedly in the past 50 years, logging and road-building methods have generally become more environmentally sensitive (USDA Forest Service and USDI Bureau of Land Management, 1994; Garman et al., 1999). The use of tractors to move logs along the ground has gradually been replaced with the use of high-lead cables to move logs above the ground. To avoid damage to the soil from hot, broadcast burns, slash is now usually piled and burned during a moist period of the year. In recent decades, trees have been replanted within a few years of harvest, and riparian zones around fish-bearing streams are left intact to act as a buffer against the effects of logging. Although the road network is extensive, more recent road construction has been performed with the objective of minimizing landslide hazards.

Assuming that logging does have an impact on erosion rates, as recent forestry regulations imply (Oregon Department of Forestry, 1997), one might expect to see a decrease in sediment yield as a result of these management changes. This trend is not discernable with the coarse resolution of the current data set, however. Insufficient data are available to assess the impact of recent logging on erosion during the November 1996 flood in the Dorena Lake watershed, but there is a possibility that improved forestry practices resulted in fewer landslides and a more subdued erosional response than occurred with the Christmas flood of 1964. Comparison of two such floods is problematic, though, because differences in the storm events and overall landscape conditions are difficult to quantify. In any case, the magnitude of the difference in sediment yield that may result from changes in logging rates or practices in the Dorena Lake watershed is too small to be detectable through the large-amplitude variations produced by climatic events and with the time and space resolution of the data at hand. This is not to say that logging has no impact on erosion rates or sediment yield in large, Western Cascades watersheds but simply that the methods used in this study were unable to discern its influence.

Ideally, one would like to compare the current sediment yield to some measure of the average sediment yield of the watershed before any logging was done. Pre- and post-logging values may differ significantly enough to be detectable even in this large watershed, whereas changes in sediment yield from relatively small variations in current logging rates are not. Unfortunately, logging in the Dorena Lake watershed began long before the reservoir was constructed, so the sediment yield of the watershed in a pristine state is not available from the 50-year sediment record in the lake.

Despite the low resolution and relatively short time frame of the data, a great deal of information was obtained by studying Dorena Lake sedimentation. The complex reservoir management style does not appear to affect the quality of this type of lake study and, in fact, was beneficial in providing direct access to the lake bottom during the winter. The distinct laminations found in the sediment deposited above low pool aided in stratigraphic correlation and enabled the calculation of sediment yield for seven different time periods. ^{137}Cs dating, in contrast, only provided sedimentation rates for three time periods; but it was nonetheless important in verifying stratigraphic correlations. The relatively young age of the reservoir was compensated to some extent by the daily records of lake level, inflow, and outflow. These records proved useful in interpreting core stratigraphy and assessing the extent to which lake sedimentation is related to hydrologic history. A better understanding of the trap efficiency of this type of flood-control reservoir by direct measurement of inflow and outflow sediment loads would greatly improve the accuracy of sediment yield calculations.

Clearly, the flood-control reservoirs of the Willamette Basin warrant further study. Although they cannot provide the length of record usually found in natural lakes, they do provide information about current sediment yield and the effects of large floods. A series of studies similar to this one on the other ten reservoir projects in the Willamette Basin could provide a useful way to compare large watersheds in the Western Cascades and give scientists a baseline for future comparisons. These watersheds differ in general susceptibility to erosion and in land use history, which may facilitate a disentangling of the effects of geology, soil, storms, and land use.

6. Conclusions

Although the flood-control reservoirs of the Willamette Basin are fairly complicated systems in terms of management and trap efficiency, study of the stratigraphy and amount of sediment in Dorena Lake proved informative. Daily records of lake inflow were useful in interpreting sediment stratigraphy and comparing the number of high-discharge days with measured sediment yields. Over the past 50 years, the Dorena Lake watershed has had an average sediment yield of 108 tons/km^2/year, but the occurrence of large flood events has had a strong effect on sediment production. Large variations in hydrologic conditions seem to have exerted a stronger influence on sediment yield than small variations in timber harvesting did. Given that fluctuations in precipitation and stream flow encompassed several orders of magnitude, the minor changes in logging rates and practices that occurred in the watershed over the past 50 years did not have a detectable impact on the data currently available. In effect, this study illustrates the difficulty of dealing with a landscape as spatially and temporally variable as the Western Cascades. While small watershed studies are perhaps too small-scale to get a sense of average process rates, large watershed studies may lack the resolution needed to differentiate between the multiplicity of influences on sediment yield. Investigation at multiple scales is thus required for a full understanding of the processes involved. Although issues of this sort will continue to plague studies about the effects of land use on sediment yield, Willamette Basin flood-control reservoirs offer a relatively quick and inexpensive avenue of approach to these problems on a regional level.

Acknowledgements

This study was supported by research grants from the Geological Society of America, the Clay Minerals Society, and the University of Oregon and by a graduate fellowship from the Environmental Protection Agency's Science to Achieve Results (STAR) program. GIS data were provided by the staff at the Cottage Grove Ranger District of the Umpqua National Forest and by Doug Oetter at the Laboratory for Applications of Remote Sensing in Ecology at the Pacific Northwest Research Station, USDA Forest Service, in Corvallis, Oregon. I thank Jerry C. Ritchie for performing the ^{137}Cs measurements at the USDA ARS Hydrology Laboratory in Beltsville, MD. I am especially grateful to Herschel Henderly and his staff at the Cottage Grove office of USACE for their invaluable assistance with the sedimentation survey and for providing information about the history of Dorena Lake. Anthony P. and Ted G. Ambers skilfully fabricated the spud used in the survey. Drafts of this manuscript were much improved by the thoughtful comments of Frederick Swanson, Rebecca Dorsey, Patricia McDowell, I.D.L. Foster, and an anonymous reviewer. My husband, Clifford P. Ambers, was a constant source of motivation and field/lab assistance throughout this project.

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