Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska

by

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Typed by David L. Beedle

AN ABSTRACT OF THE THESIS OF

David L. Beedle for the degree of Master of Science in Forest Engineering presented on August 28, 1991.

Title: Physical Dimensions and Hydrologic Effects of Beaver Ponds on Kuiu Island in Southeast Alaska

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Robert L. Beschta

Dimensional characteristics of 44 beaver dams and ponds on Kuiu Island in Southeast Alaska were determined to evaluate the hydrologic effects of these structures on peak flows. The study area consisted of low gradient, incised streams in broad U-shaped valleys. Pond routing simulations were conducted using four return intervals (2-, 10-, 25-, and 50-year) and seven watershed sizes through medium- (752 m^2 of surface area) and large-sized (6002 m^2) beaver ponds. The annual precipitation during field data collection was below normal resulting in a need to estimate winter pond conditions from summertime measurements.

The average dam length and height was 32 m and 0.7 m, respectively. The average winter pond surface area and volume was 2,140 m^2 and 1,250 m^3, respectively. Pond volume was significantly related ($p = 0.05$) to surface area (r^2 =

0.91). Dam and pond dimensions were influenced by local stream and landscape characteristics.

Simulated peak flow routing through a beaver pond was accomplished using the Modified Puls method to calculate the theoretical percentage reduction in storm peak flows due to beaver dams and ponds. A triangular inflow hydrograph with the time to peak at 1/2 the total hydrograph duration was used. Thirty inflow hydrographs of various durations and peak discharges were routed through each pond to determine their effect on peak flows.

Beaver dam surface profiles are very flat. This resulted in large outflow rates over a dam with little increase in pond head. Single, full beaver ponds were found to theoretical reduce peak flows by no more the 5.3%, regardless of the return interval or watershed size. The shape of the outflow hydrographs were the same as the inflow hydrographs, with only a 10 or 15 minute delay in the time to peak and slightly increased duration. Reductions in peak flows became increasingly large as the number of ponds in a series increased. Five large-sized beaver ponds in series reduced the storm peak flow by 14% for a 2-year event, but only 4% for a 50-year event.

Detention storage effects of stormwater discharging over a beaver dam and onto the floodplain was not addressed in this research.

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INTRODUCTION

Beavers (Castor canadensis) are one of the few animals that can greatly alter the environment in which they reside. Therefore, the physical aspects of streams and riparian areas can be vastly different depending of the presence or absence of beavers. Pond resulting from the construction of beaver dams can inundate riparian areas and flood plains, change plant succession, raise groundwater elevation, alter stream hydraulics, and possibility influence stream hydrology.

The presence of beavers can result in a wide spectrum of resource benefits. Greater channel water depths and slow stream velocities can provide increased winter habitat for juvenile fish. Fish production may also increase after damming in cooler regions due to pond warming from solar energy entering the water over a larger surface area. Downstream water quality may be improved by trapping sediment in ponds during high flows or as a result of upstream management activities (e.g., road construction and/or harvesting). Prolonging the nutrient retention time in ponds may also improve primary productivity.

Although forest management practices in riparian areas can influence important stream and riparian characteristics related to fisheries, water quality, and recreation activities, the presence of beavers may complicate potential management scenarios. Furthermore, not all beaver activities can be considered beneficial. For example, summer stream temperatures may increase due to the inability of riparian vegetation to shade a significant portion of the pond surface. This condition may not be desirable for low gradient streams that normally experience warm temperatures. The ponding of streams may flood hiking trails and create safety hazards due to dead and partially fallen trees. The presence of beavers may decrease water quality for domestic uses (giardia). The failure of dams during high flows may also temporarily decrease water quality by releasing sediment into a stream and by increasing channel erosion. Potentially, this sediment can degrade downstream spawning areas or overwintering pools by depositing in these areas.

The reintroduction of beavers into streams throughout the western United States is gaining popularity with many fisheries and wildlife biologists, recreation managers, and the general public. Many of these groups rationalize beaver reintroductions on the basis that they may provide a cheap alternative to stream and riparian rehabilitation projects. However, few research studies have dealt with the affects beavers may have on watershed hydrology.

The planning of management activities along streams frequently involves an assessment of potential hydrologic affects. Decisions affecting streamside management activities may identify hydrologic effects of beavers, that are assumed to be factual, as a justification for particular decisions. For example, several published papers indicate peak flows are dampened by beaver dams (Scheffer, 1938; Reitzer, Swope, Remington, and Rutherford, 1956; Neff, 1957; Allred, 1980; and Parker, et al., 1985). Supporting data that would substantiate this hydrologic effect is lacking.

Determining the relationships between beaver ponds, dams, and physical watershed characteristics should help in assessing the hydrologic affects of beaver dams on streamflows. In conjunction with a streamflow routing model, information on dam and pond dimensions may be used to prove or disprove the theory that beaver dams reduce peak flows.

This study has two major objectives. The first is to evaluate relationships between the selected physical characteristics of beaver dams and ponds and the physical characteristics of the adjacent watersheds. The second objective is to assess the potential changes in peak flows associated with beaver dams and ponds. The second objective is accomplished by utilizing field data on beaver dams and ponds, in conjunction with a mathematical routing model. If it can be demonstrated that peak flows are significantly altered, this could provide important information for future decisions affecting beaver management and forest management practices along streams.

REVIEW OF LITERATURE

The influence of beavers upon the physical characteristics of stream and riparian systems have often been overlook by scientists and the general public. To date, much of the research has dealt with the biology and terrestrial habits of beavers. Research on aquatic systems has typically focused on fish-beaver interactions (Call, 1966; Sanner, 1987), examined deposition in ponds, or evaluated nutrient cycling (Ford and Naiman, 1988). Pond volumes and/or surface areas have been estimated (but not measured) in several papers dealing with the amount of sediment trapped in ponds (Ruedemann and Schoonmaker, 1938) or ecological effects of beavers (Neff, 1957).

Occasionally the dimensional aspects of beaver dams and ponds have been reported, although such information typically represents an associated issue in most research efforts. For example, fisheries-beaver interaction studies have contributed dimensional information, because pond size is an important factor affecting the productivity of the fisheries resource (Rabe, 1970). Habitat suitability index and site selection studies have provided additional information (Howard and Larson, 1985). These type of assessments often concentrate on selected physical parameters (i.e., stream gradient, valley width, stream width, and annual average water fluctuation) with most other parameters related to vegetation composition, stem diameter, and proximity to water.

Stream Gradients

Most beaver studies report stream gradients associated with a study area because it is an easily measured watershed characteristic associated with the occurrence of beavers. Because much of this data is from case studies (Avery, 1983; Medin and Torquemada, 1988), only a selected sample of research studies will be presented in this section.

The study by Scheffer (1938) is an example of early stream gradient evaluations. His study of beaver meadow complexes on two streams in Washington indicated stream slopes of 2.5% over a 622 m reach. Smith (1950) evaluated 180 dams in the Rocky Mountains of Colorado and found that gradients ranged from 0.5% to 10.5% with 48% of the dams associated with gradients of 0.5% to 4.5%. In a more comprehensive study, Reitzer et al. (1956) reported that in Colorado 91% of the beaver dams occurred where valley gradients were less than three percent; all active dams were in valleys with gradients of 15% or less. Based on the literature, stream gradients of 15% may represent an upper limit of site selection.

Dam and Pond Dimensions

Case studies contained the majority of the published information on dam and pond dimensions. For example, Morgan's (1868) detailed zoological study of beavers along a railroad right-of-way in Michigan also indicated average dam lengths of 19 m (Table 1). Dugmore (1914), in a nontechnical book that was written to help save the beaver from over-harvesting in Canada, reported dam lengths ranging from 91 to 152 m. Scheffer (1938), studying beaver meadow complexes in Washington, reported dam lengths and heights averaging 13 and 0.87 m, respectively. Ruedemann and Schoonmaker (1938), reported maximum dam lengths and heights by other authors in a geological review on the effects of beavers on valley formation. Smith (1950), studying the effects of runoff and gradient on beavers in Slate Creek, Colorado, reported an average dam length of 26.5 m. A waterfowl management study by Beard (1953) reported dam length and heights averaging 13.7 and 0.91 m, respectively. Bryant (1983), studying the relationship between beaver ponds and coho salmon (<u>Oncorhyncus</u> <u>kisutch</u>) habitat, measured dams in the Blind slough, Kadashan, and Trap Bay Creek, Alaska. The dams averaged 23.5 m long and 1.0 m high as measured along the downstream face. McComb, Sedell, and Buchholz (1990), studied beaver site selection on Long Creek in the Coast Range of Oregon and found dam heights averaged 0.55 m.

Table 1. Beaver dam dimensions (meters) reported in the literature.

Dam Length (m)		Dam Height (m)		Number of Dams	Reference
Ave.	Range	Ave.	Range		
19	--	--	0.3 - 1.9	9	Morgan (1868)
--	91 - 152	--	--	--	Durgmore (1914)
13	2 - 37	0.9	0.3 - 1.5	22	Scheffer (1938)
28	--	2.1	--	1	" "
27	--	--	--	30	Smith (1950)
14	--	0.9	--	1	Beard (1953)
24	5 - 46	1.0	0.8 - 2.2	7	Bryant (1983)
--	--	0.6	--	14	McComb, Sedell, and Buchholz (1990)

Pond dimensions have not been reported in the majority of beaver studies. Even those studies that have reported pond dimensions, surface areas and storage volumes were usually estimated. Scheffer (1938), found pond volumes averaging 81 m^3 during the summer-low and 2,600 m^3 during the wetter fall conditions (Table 2). Yeager and Hill (1954), in a study of beaver management problems in the western United States, reported a 5.5 m high dam having a storage volume of 286,000 m^3. In southeast Alaska, Bryant (1983), reported pond surface areas averaging 1,150 m^2. Sanner (1987), on the Kenai Peninsula of Alaska, measured stream and pond dimensions to determine the relationship between beavers and coho salmon habitat. She found an average surface area of 7,400 m^2 with a range from 500 to 17,900 m^2. Bruner (1989), studying beaver and fisheries interactions in the Oregon Coast Range, reported pond volumes and surface areas averaging 237 m^3 and 507 m^2, respectively. Also in the Coast Range, McComb, Sedell, and Buchholz (1990) reported an average surface area of 167 m^2. Johnston and Naiman (1990) reported that pond size is often a function of age, as the age of the structure increases the size of the pond increases. However, most studies provided little information about seasonal or yearly trends.

From the limited amount of information in the literature, pond dimensions have been shown to vary over

Table 2. Beaver pond dimensions (meters) reported in the literature.

Volume (m^3)		Surface Area (m^2)		Number of	
Ave.	Range	Ave.	Range	Dams	Reference
81^a	--	--	--	22	Scheffer (1938)
2600^b	--	--	--	1	" "
286000	--	--	--	1	Yeager and Hill (1974)
--	--	1150	29 - 5047	7	Bryant (1983)
--	--	7400	500 - 17900	2	Sanner (1987)
237	127 - 347	507	367 - 650	2	Bruner (1990)
--	--	167	--	14	McComb, Sedell and Buchholz (1990)

a = Summer volume
b = Fall volume

several orders of magnitude. However, the reported dam and pond dimensions should only serve as approximate values due to the limited number of examples and the highly variable nature of pond sizes.

Reservoir Routing

The routing of water through a beaver pond has no direct equivalent in the hydraulic engineering field. Beaver dams are rough, broad-crested, and leaky. Assuming that pond outflows over a dam can be represented by weir equations, then overflow discharges are determined by the shape of the crest, weir length, and form. Reservoir storage is dependent on the interaction between dam characteristics and local topography to develop stage-discharge and stage-storage relationships.

Relatively little research has examined the discharge characteristics of irregular shapes broad-crested weirs. USDI Geological Survey (1903), studied 10 irregular shaped weirs to obtain better predictions of discharge at gaging stations (King and Brater, 1963). The study used the basic broad-crested weir equation and determined the changes in discharge coefficients for various weir shapes. The equation for a broad-crest weir is:

$$Q = CLH^{\frac{3}{2}} \tag{1}$$

where Q is discharge, C is the discharge coefficient, L is the weir length, and H is the head above the weir.

Many mathematical models are available for routing water through a reservoir. These models generally require knowledge of the stage-discharge and stage-storage relationships. The stage-discharge relationship is determined solely by the characteristics of the outflow structure whereas the stage-storage relationship represents the available storage at any given stage and is primarily a function of local topography. The basic reservoir mass balance equation for routing water through a reservoir is:

$$INFLOW - \Delta STORAGE = OUTFLOW \qquad (2)$$

where Inflow is discharge multiplied by change in time ($Q_1\Delta t$), Outflow is discharge multiplied by change in time ($Q_2\Delta t$), and Δstorage is the change in storage during the time period (S_2 - S_1). Based on this equation, the Modified Puls and Stage-Indication methods for routing water through a reservoir have been developed (McCuen, 1989). These methods are based on the equation:

$$\frac{1}{2}(I_1 + I_2)\Delta t + (S_1 - \frac{1}{2}O_1\Delta t) = (S_2 + \frac{1}{2}O_2\Delta t) \qquad (3)$$

where I is inflow (discharge), O is outflow (discharge), S is storage (volume), and Δt is change in time. Subscripts 1 and 2 represent conditions at the beginning and end of a particular time step, respectively. Knowing the conditions at the start of the time step, stage-discharge relations, stage-storage relations, and inflow at the end of the time step, S_2 and O_2 can be estimated.

The Stage-Indication method requires a storage-outflow relationship and an outflow versus $(S + \frac{O}{2}\Delta t)$ relationship. This procedure represents an instantaneous outflow method based on finite differences and requires the inflow hydrograph to be approximately linear between inflow hydrograph data points (McCuen, 1989).

The Modified Puls method is one of the most common methods of reservoir routing. It utilizes the same routing equation (2) as the Stage-Indication method, but the outflow versus $(\frac{2S}{\Delta t} + O)$ relationship is used instead. This method is also an instantaneous outflow model that requires linearity between inflow hydrograph time steps (Puls, 1928).

Two other methods for reservoir routing include the Coefficient and Mass-Curve methods. The Coefficient method is one of the easiest methods to route water through a reservoir. This model assumes storage is directly proportional to outflow: $S_2 - S_1 = K(O_2 - O_1)$ where K is equal to the reciprocal of the slope of the storage curve (Chow, 1964).

The Mass-Curve method can be performed both graphically or numerically and is considered a relatively versatile routing model. The model requires the development of elevation-storage and elevation-discharge relationships. The Mass-Curve approach also involves a trail and error process to determine the outflow hydrograph. The routing equation for this method is $MI_2 - (MO_1 + \bar{O}\Delta t) = S_2$ where MI_2 is mass inflow at time 2, MO_1 is mass outflow at time 1, $\bar{O}$ is average rate of outflow during the routing interval, and S_2 is storage at time 2 (USDA, Soil Conservation Service, 1971).

All the above models use mass-balance techniques to obtain outflow hydrographs. Differences between methodologies are in the inflow hydrograph assumptions and the equations used to obtain stage and outflow at the end of each time step.

STUDY AREA

This study was conducted on Kuiu Island in the Tongass National Forest of Southeast Alaska (Figure 1). Kuiu Island is located at 54°45′ north latitude, 134°00′ west longitude, or 190 km south of Juneau and 96 km west of Petersburg. The island is approximately 100 km long and 38 km wide at its broadest point and has a surface area of roughly 1,900 km^2.

Kuiu Island is part of the Kupreanof Lowlands physiographic province (Selkregg, 1974). The northwest portion of the island consists primary of unconsolidated deposits of paleozoic rock (Figure 2). The Port Camden area is composed of unconsolidated deposits of tertiary rock consisting of volcanic basalt flows and nonmarine sandstone, coal, conglomerate, and shale. Saginaw Bay was formed by the only fault present on the northern portion of the island. This area has paleozoic rock and paleozoic to middle mesozoic rock consisting of chert, limestone, shale, volcanics, and conglomerates. The mountains north of Rowan Bay are composed of paleozoic, intrusive, and jurassic to cretaceous rocks. The study area is limited to watersheds north of a line between Bay of Pillars and Port Camden (Figure 2).

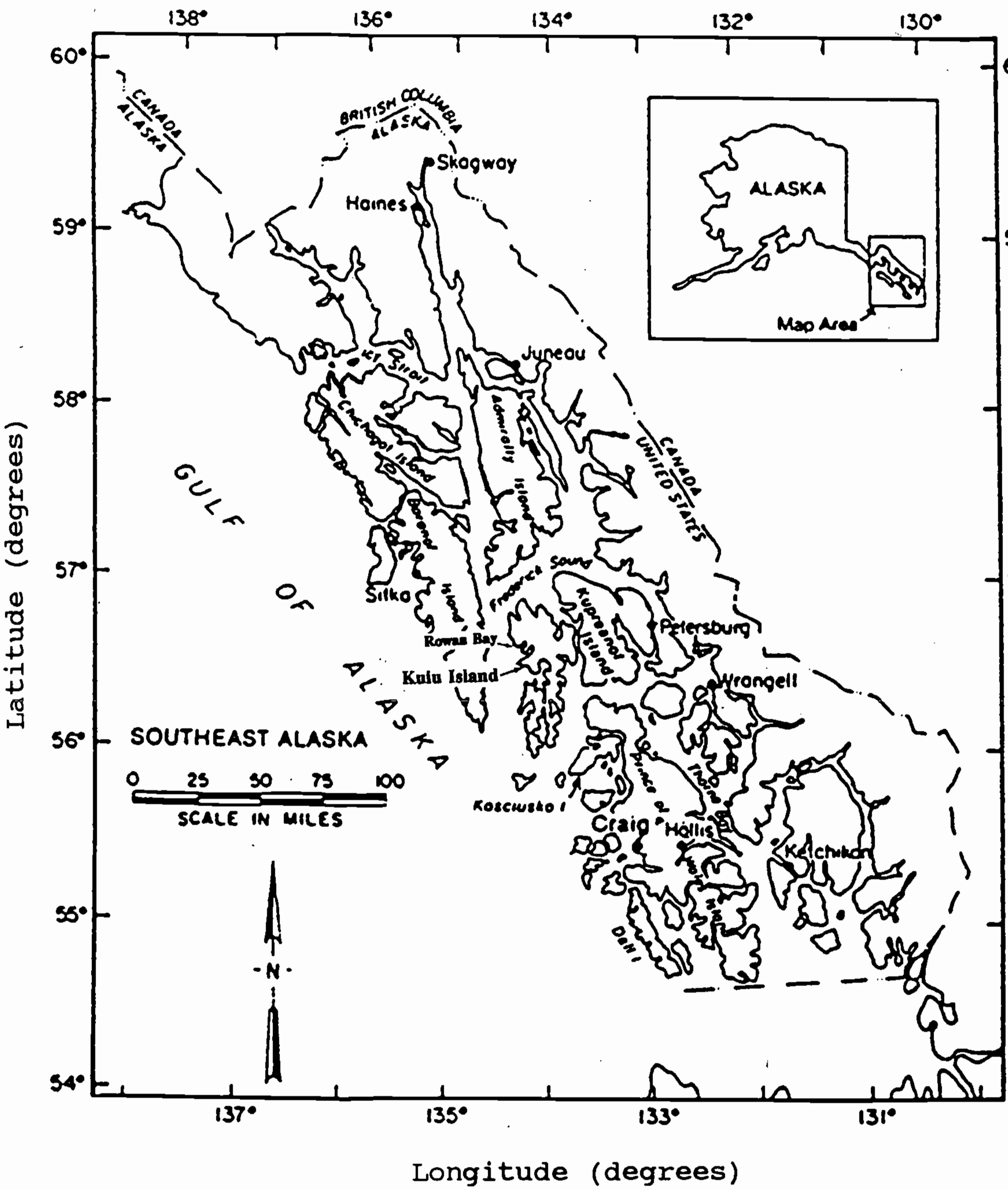
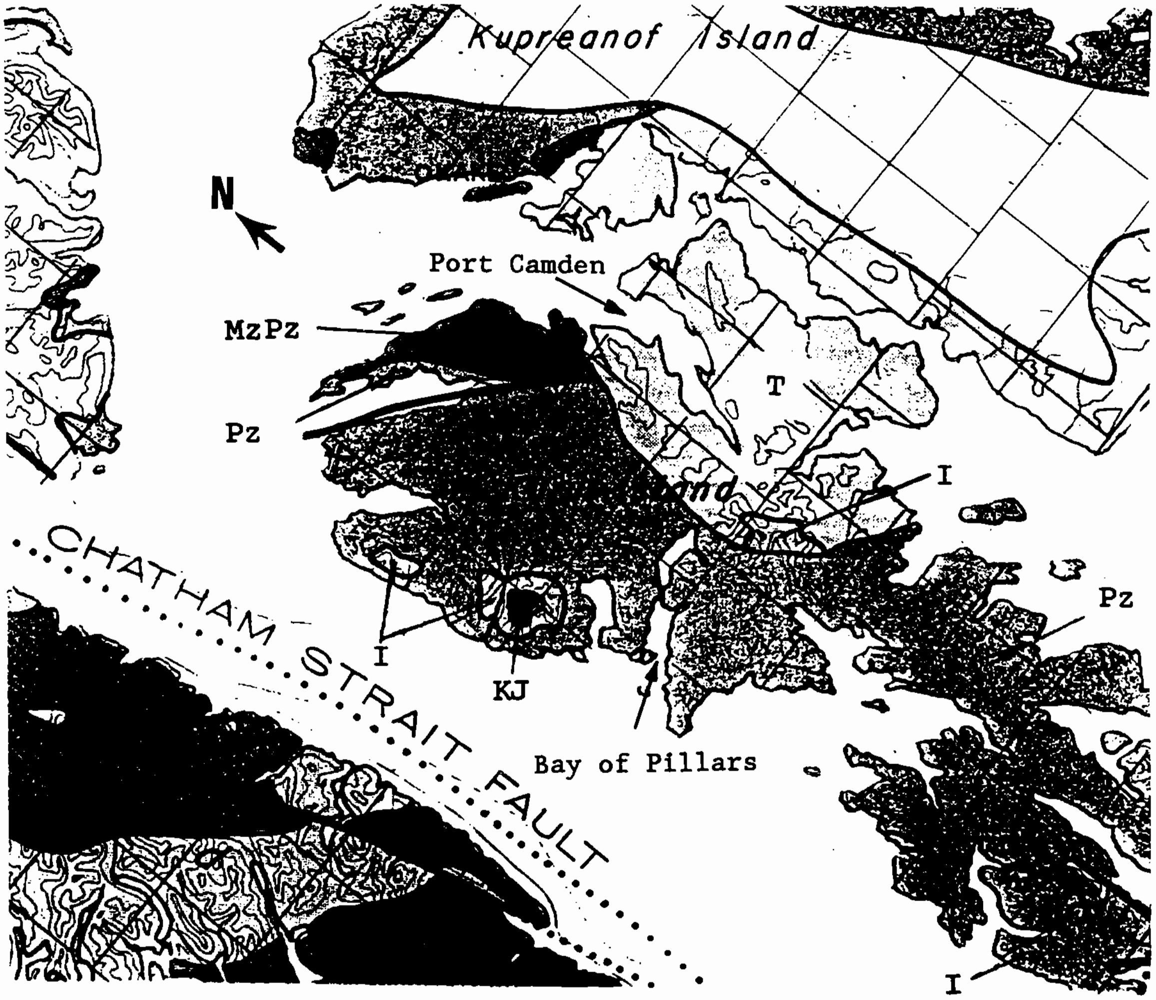


Figure 1. Location map of Southeast Alaska.



Scale 1 : 107,400

Pz - Paleozoic
MzPz - Paleozoic to middle Mesozoic
T - Tertiary
I - Intrusive
KJ - Jurassic to Cretaceous

Figure 2. General bedrock formations of northwest Kuiu Island taken from Billings, Swanston, and Bergmann (1971).

Except for the highest mountain peaks, Kuiu Island has been intensely glaciated. This has created steep-walled U-shaped valleys covered with glacial till to about 450 m of elevation. Glacial outwash and alluvial material of unknown depths cover the valleys, but the bedrock is close to the surface along broad valley wall benches. The island is in glacial rebound at a rate up to 2 to 4 cm (0.8 to 1.6 in) per year (Selkregg, 1974).

Southeast Alaska has three broad categories of soils: well drained soils, mineral soils of impeded drainage, and organic soils (Selkregg, 1974). The general types of soil on Kuiu Island are: (1) well drained, strongly acid soils, very dark subsoil, and shallow bedrock and (2) well drained strongly acid soils, very dark subsoils with slopes less than 12 percent and very gravelly. The erosion potential for both soils is moderate to high (Selkregg, 1974). Valley bottoms are dominated by poorly drained organic soils that are occasionally overlaid with fine texture lake or marine deposits. The valley bottoms of Kuiu Island consist of Kina, Maybese, Turekan, Kupreanof, and Gunnuk soils series. The hillslopes consist of Woewodski soil series, which are mostly well drained soils. Many V-shaped valleys consist entirely of well drained soils (Billings, Swanston, and Bergmann, 1971).

There are seven major drainages on the northern portion of the island (Bay of Pillars, Rowan Bay, Security

Bay, Dean Creek, Saginaw Bay, Kadake Creek, and Port Camden). Kadake Creek is the largest stream system with a watershed area of 6.2 km^2. Most of the streams on the island have incised to some degree. Streams generally have vertical banks with forest or grass and sedge cover on floodplain benches. The U-shaped valleys have a wide range of stream gradients throughout the watersheds. Headwater reaches can be steep (i.e., >15%), however, gradients typically become much lower (i.e., <1.5%) when streams reach the main valley (Harris et al., 1974). Streams not affected by beaver activities generally have gravel substrates.

The forest vegetation cover type is classified as Western Hemlock (Tsuga heterophylla)-Sitka Spruce (Picea sitchensis). Associated tree species include Alaska-cedar (Chamaecyparis nootkatensis), mountain hemlock (Tsuga mertensiana), red alder (Alnus rubra), and lodgepole pine (Pinus contorta). The understory generally consists of huckleberry (Vaccinium spp.), skunkcabbage (Lysichitum americanum), Devil's-club (Oplopanax horridus), and salmonberry (Rubus spectabilis). The island is continuously forested except on the valley floors where a matrix of forest, grass and sedge (Carex spp.), and muskeg areas occur. The muskegs consist primarily of Sphagnum moss (Sphagnum spp.) and can be 6 m or greater in depth. Sphagnum may be hydrologically important during rewetting periods due to the fact that it can hold 15 to 30 times its own weight in water (USDA, Forest Service, 1989).

Southeast Alaska has a maritime climate. Proximity of the ocean keeps most of the islands and near-shore mainland cool and moist year around. The yearly movement of the jet stream results in seasonal precipitation differences with winters generally being wetter than summers. During the summer the jet stream moves northward over Southeast Alaska, but shifts toward lower British Columbia and the Pacific Northwest during the winter. The annual precipitation of Southeast Alaska ranges from 1,520 to 5,080 mm per year depending on the orographic effectiveness of local mountains. There are an average of 275 cloudy and 43 clear days per year (Harris et al., 1974). The moderating effect of the ocean also creates a narrow range of seasonal and daily temperatures changes; daily temperature fluctuations are usually less than 5°C (9°F).

The mean annual peak flow is approximately 1.09 cubic meters per second per square kilometer (CSK) or 100+ cubic feet per second per square mile (CSM). The mean low monthly flow is 0.05 CSK (5 CSM) (Feulner et al., 1971). The largest peak flows are generally in the spring due to snow melt runoff and in July, August, or September when rainfall amounts are often high.

POND ONTOGENY

Pond shape and developmental sequence (Ontogeny) can have important effects on total storage. Hence, the capability of a given pond to influence peak flows may be a function of the interrelationship between these factors.

Local geomorphic features influence the shape of beaver dams and the resultant storage volume of associated ponds. The stage-discharge and stage-storage relationships are tied intrinsically to the shapes of the dam and pond. Thus, different shapes may have different hydrologic responses to a storm event depending on the availability of storage and rate of outflow. Dam and pond shapes that allow the maximum time rate of storage per unit of inflow will have the greatest effect on altering peak flows. Conversely, a pond that undergoes little change in storage before water is overflowing the entire dam will have a small effect on peak flows.

The extended presence of a dam in a particular location causes the pond to go through developmental changes through time. From field observations, it appeared that there were six basic phases of ontogeny on Kuiu Island. The phases were defined by the presence and condition of trees and logs within the pond. These designations are important because the six developmental stages may have different hydrological responses to a storm hydrograph.

The first phase is represented by a new pond with mostly live trees still present within the pond. Phase 2 is characterized by the presence of primarily standing dead trees with several of which have broken tops. The third phase has more broken tops than in Phase 2 and a larger organic load of log and branch debris in the pond. The fourth phase is characterized by the absence of standing trees in the pond and the large organic debris load is typically lower than in Phase 3. The fifth phase is represented by a pond that is almost completely void of large organic debris. Phase 6 is a pond that is essentially filled with sediment and has emergent aquatic vegetation covering most of the bottom. This last phase most likely represents the initiation of a beaver meadow. The sequence of stage development is not always continual. The development can cycle back to an earlier stage if beavers cease to maintain a dam or raise the pond level and flood the surrounding trees.

METHODS

Field measurements of beaver ponds and dams on Kuiu Island were conducted during August of 1989. Sites were selected to encompass the full range of pond and dam types over various watershed settings. Because of access limitations, sites were within a few hundred meters of existing roads. In addition to stream and watershed characteristics, physical measurements at each site were organized into two principal categories: (1) beaver dam dimensions and anchoring mechanisms, and (2) beaver pond dimensions and associated forest vegetation.

The level of significance for all statistical evaluations were assigned at the 0.05 level. The 0.05 alpha level identifies the tail region that the null hypothesis may be rejected. This alpha was selected as a reasonable level due to the variability of the data and exploratory nature of this project. Distribution fitting was accomplished using a Chi-square test on a PC statistical package. Reductions in peak discharge were determined to be significant if the reduction was greater than 10% of the original hydrograph peak discharge.

Stream and Watershed Characteristics

Several landscape physical features were measured to assist in the characterization of terrain types associated with the beaver dams and ponds on Kuiu Island. These measurements were used to determine of relationships existed between landscape features and beaver dam and pond dimensions.

Valley width was defined as the cross-sectional distance between the toes of the first floodplain bench or terrace surface that would constrain a pond. Stream gradient was measured to the nearest degree, using a clinometer and a survey rod, whenever an unrestricted reach occurred downstream of a studied dam. Stream cross-sectional area and standing water volume were determined by three cross-section transects downstream of a dam. Channel width was defined as the distance across the top of the bankfull channel. The distance between transects was usually three meters. In areas where unrestricted channel length below a pond was limited, transect spacing was reduced to one or two meters.

Dam Anchors

Dam anchors represent large structural elements that are used by beavers to reinforce or aid in holding a dam in place. Anchors on Kuiu Island consisted primarily of down-logs and standing trees. Measurements of down-logs consisted of length and large-end diameter. Whereas measurements of standing dead and living trees consisted of diameter at breast height (DBH), species, and decay class (Table 3).

Pond Tree Characteristics

The large amount of dead organic material produced by beavers flooding forested areas may have important affects on fish habitat. Furthermore, such material may influence channel stability if a dam were to wash out. Standing trees and snags were characterized the same as dam anchors (Table 3). Live trees are also coded by species (Table 4). For a down-log to be recorded, (1) at least 50% of its total length had to reside within the pond and (2) its diameter had to be greater than 15 cm (6 in). The large-end diameter and total length were measured for every down-log meeting these criteria.

Summer-Stage versus Winter-Stage Conditions

According to U.S. Forest Service employees on Kuiu Island, stream flows during August of 1989 were below the normal summer flows and pond stages were also correspondingly low. Due to the reduced volumes of water in storage, water had to be "mathematically added" to simulate winter storm conditions for pond routing. Mathematical adjustment of pond dimensions were accomplished by incrementally increasing the pond elevation and calculating the associated increase in pond volume and

Table 3. Decay classes for standing trees associated with beaver dam anchors and pond vegetation on Kuiu Island, Alaska.

Decay Class	Living or Dead	Percent of bole broken off
1	Living	NA
2	Dead	< 1/3
3	Dead	1/3 < % < 2/3
4	Dead	> 2/3

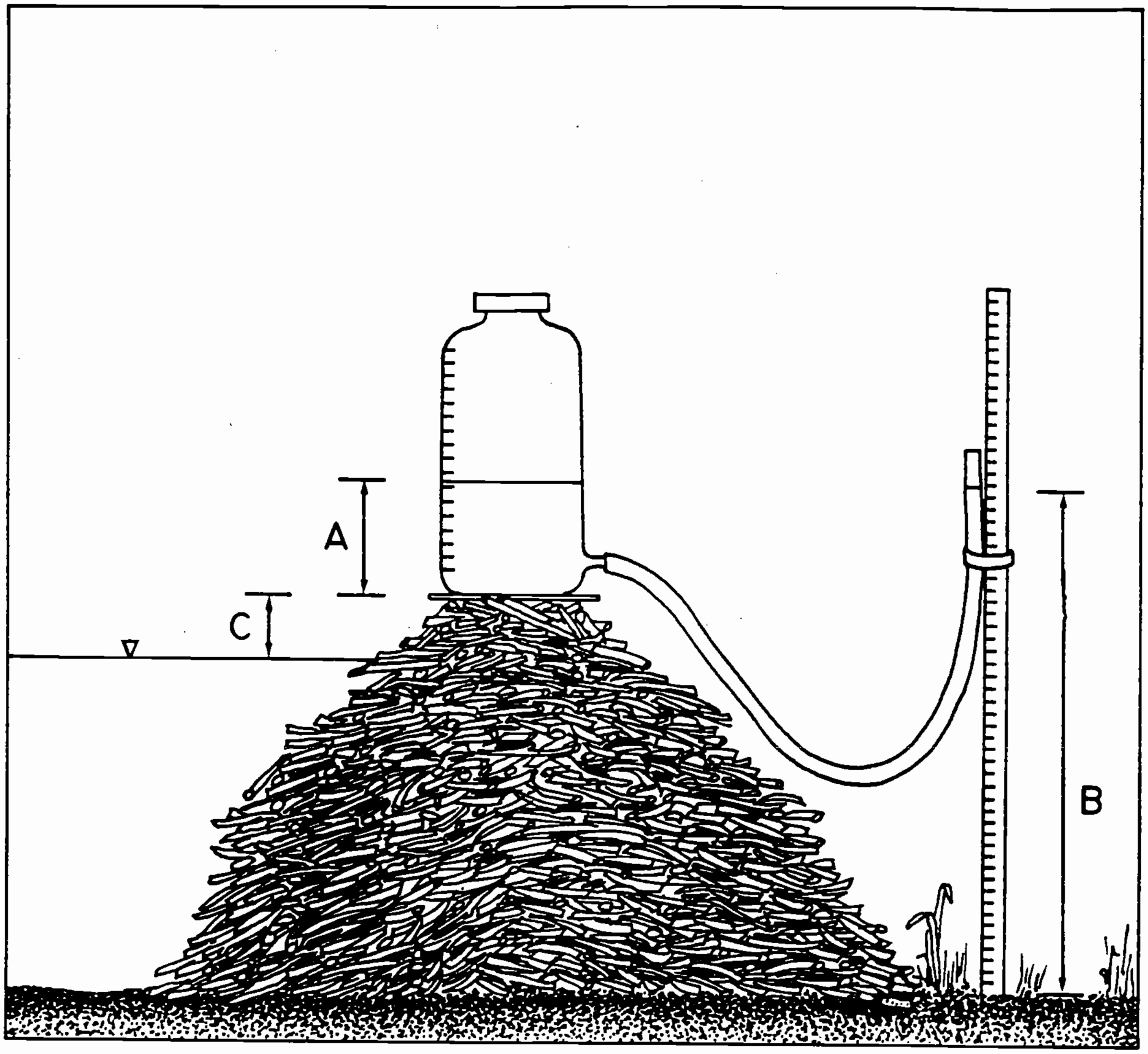
Table 4. Pond tree species code for Kuiu Island, Alaska.

Species	Code
Sitka spruce	1
Western hemlock	2
Red alder	3
Dead/Unknown	4
Alaska Cedar	5
Mountain hemlock	6

surface area. Dimensions present during field sampling are defined as "summer-stage". The mathematically adjusted dimensions are defined as the "winter-stage".

Dam Characteristics

For each beaver dam, the length, height, and base width were measured at intervals along the dam. Dam length was determined by positioning a cloth tape along the top contour between detectable ends of the dam. Dam height was measured by using a water-level device that indicated the elevation difference between the ground and the top of the dam (Figure 3). Dam height was defined as the elevation difference between the top of the dam and the immediate downstream area not disturbed by beaver activities. In areas where a downstream pond flooded the area immediately below the dam, the pond surface elevation was used to define the base of the dam. This measurement protocol maintained consistency in areas that may have been disturbed by beaver activities. Dam heights were determined by subtracting the height of the water in the bottle from the recorded height on the survey rod. Height measurements were obtained at selected intervals along the dam avoiding trees, logs, and disturbed ground to achieve the best readings. The elevation difference between the top of the dam and the pond surface was also measured to determine the longitudinal profile of the dam for weir



Height of water in bottle = A

Dam Height = B-A

Pond Height = B-A-C

Figure 3. Schematic of a water bottle system.

calculations (Figure 3).

The base width for each dam was measured near the center of the dam. The upstream edge was defined as the slope break or the location where dam material was no longer found in the substrate.

Pond Characteristics

Beaver pond dimensions are essential to determine the storage volumes required for pond routing. Pond length was defined as the linear distance from the top of the dam to the farthest upstream influences of the pond. If the dam was concave or convex the distance was measured from the midpoint between the farthest upstream and downstream points of the dam. Pond length was measured by placing a tape parallel to or through the middle of the pond. Depth transects were conducted perpendicular to the longitudinal axis of the pond (Figure 4). The first transect was placed close to the dam due to the higher proportion of volume at that location. The distance between the remaining transects were usually even intervals.

Pond depth measurements were obtained at intervals across the pond; location was influenced by the presence of logs, trees, or bottom topography. Depths were determined by lowering a survey rod vertically until the rod contacted the surface of the bottom sediments. The distance from the shore was then measured with a model 100 Range Finder or a

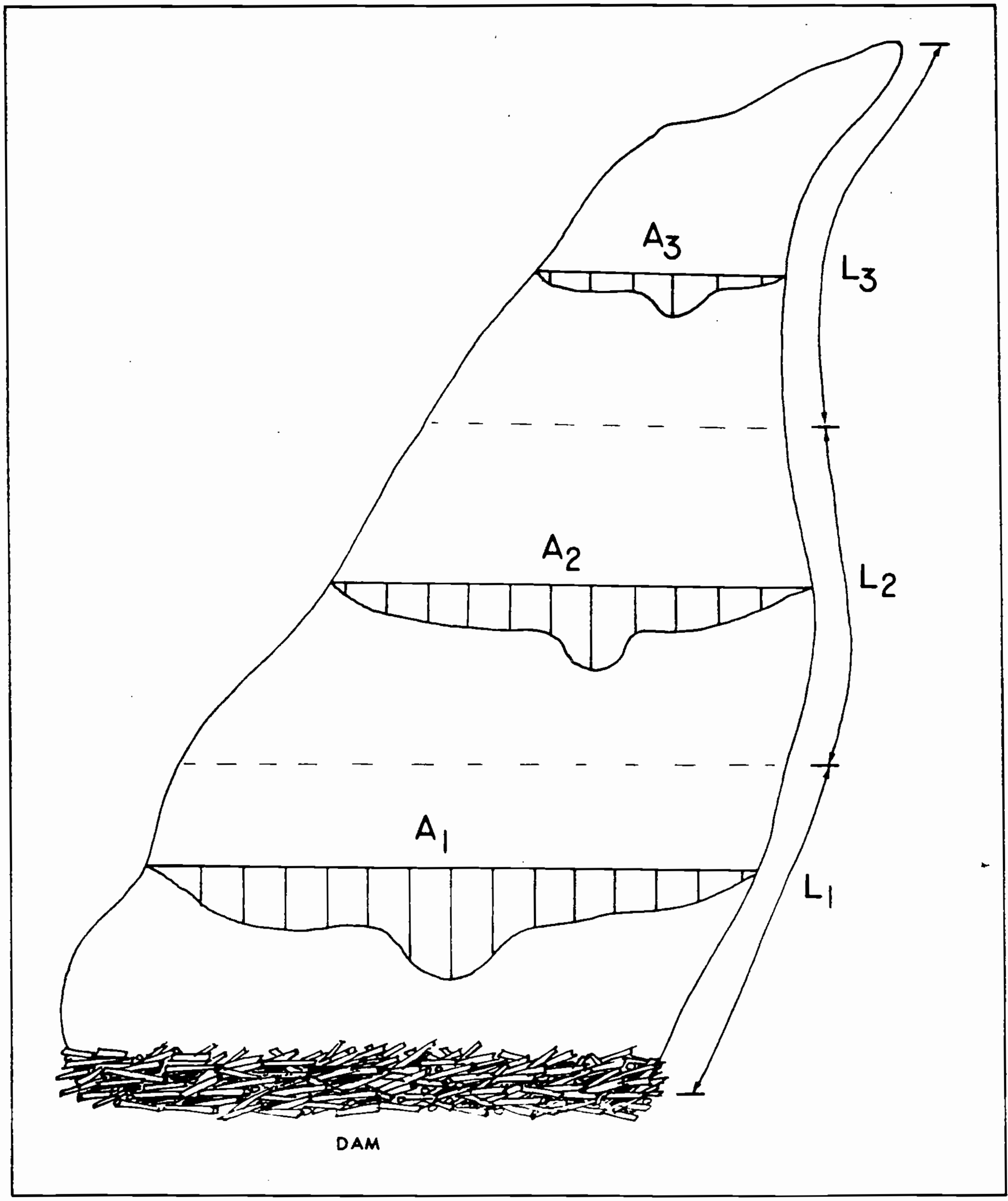


Figure 4. Layout of pond measurements.

Sonin 250 Electronic Distance Measuring Instrument (The use of trade names does not constitute an endorsement of these products).

Routing Model

The Modified Puls method was selected for beaver pond routing because of the ease of use, author's familiarity with the model, and agreement with existing inflow hydrograph assumptions stated in the literature review section. The outflow discharge was determined from the outflow versus stage and outflow versus $(\frac{2S}{\Delta t} + O)$ relationships. This relationship was calculated from equation 3. These relationships were piecewise linerized into two or three segments to fit the mathematical model. The Modified Puls method for routing flows through ponds has an inherent error of about 4% (McCuen, 1989). The routing model was run by the author using a spreadsheet on a PC computer.

For evaluating the effect of beaver dams and ponds on peak flows, an inflow hydrograph was derived from a 2- to 5-year storm event at Trap Bay Creek on Chichagof Island, Alaska (Estep, 1982). A triangular shaped hydrograph was formulated that best portrayed the peak of the Trap Bay Creek hydrograph (Table 5). This shape was assumed to represent a 5-year event on Kuiu Island. Peak flows for

Table 5. Unit hydrograph ordinates for a 5-year event, Trap Bay Creek, Alaska.

Time (hr)	Ordinates
0	0
0.083	0.017
0.167	0.034
0.250	0.05
0.333	0.066
0.417	0.083
0.05	0.01
1.0	0.194
1.5	0.3
2.0	0.4
2.5	0.5
3.0	0.6
3.5	0.7
4.0	0.794
4.5	0.894
4.583	0.912
4.667	0.930
4.750	0.947
4.833	0.965
4.917	0.982
5.0	1.0
5.083	0.982
5.167	0.965
5.250	0.947
5.333	0.930
5.417	0.912
5.5	0.894
6.0	0.794
6.5	0.7
7.0	0.6
7.5	0.5
8.0	0.4
8.5	0.3
9.0	0.194
9.5	0.1
9.583	0.083
9.667	0.066
9.750	0.05
9.833	0.034
9.917	0.017
10.0	0

the 2-, 10-, 25-, and 50-year events on Kuiu Island were calculated using the predictive equations for the Tongass National Forest from the USDA Water Resources Atlas (USDA Forest Service, 1979). Six watershed areas, that ranged from 0.004 km^2 to 0.6 km^2, were used to calculate peak flows for medium- and large-sized beaver ponds. The shape of each storm hydrographs were assumed to be proportional to that of the 5-year event hydrograph (Figure 5). Total hydrograph duration for each return interval was determined from Figure 5.

The nearest gaging station to the study area was Rocky Pass Creek (15087590) on the east side of Kuiu Island. The storm hydrograph for this creek was slightly broader and longer than the Trap Bay Creek hydrograph. The Trap Bay watershed was steeper with larger impervious areas resulting in a sharper, shorter duration hydrograph. The Trap Bay hydrograph was used because of the known return interval and the sharp peak that best represented a triangular storm hydrograph peak.

The outflow characteristics for a beaver dam were determined by assuming the structure consisted of a series of adjoining rectangular broad-crested weirs. The length and elevation of each weir was based on field measurements that identified elevations along the crest of the dam. From these measurements, weir height versus cumulative dam length was plotted. From this plot a series of broad-

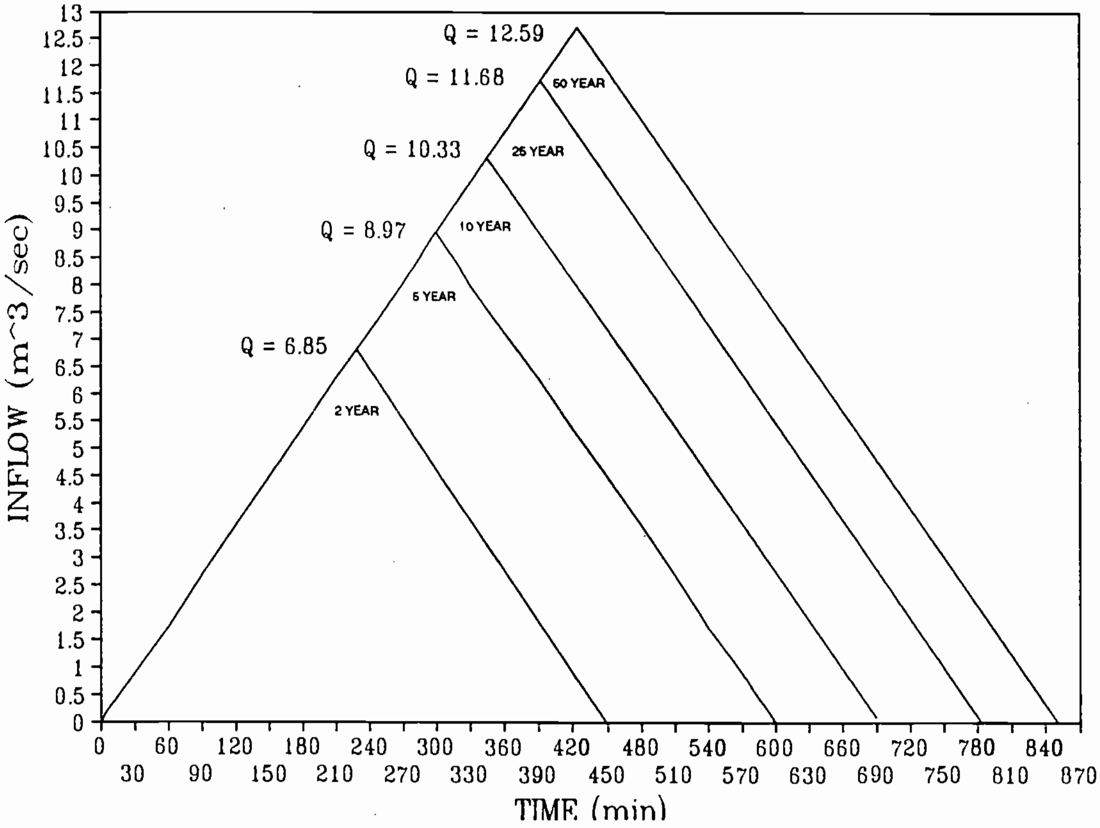


Figure 5. The 2-, 5-, 10-, 25-, and 50-year event inflow hydrographs for a one square kilometer watershed area on Kuiu Island, Alaska.

crested weirs were established. Midpoint elevations were used to determine the elevation for each weir surface. Stage-discharge relationships for individual weirs were computed using Figure 5-16 in the Handbook of Hydraulics (King and Brater, 1964). Discharge coefficients are for smooth surface and changed with head above the weir (Table 6). The overall stage-discharge relationship for a dam was obtained by summing discharges from each weir.

Modeling Assumptions

1) A 10 hour triangular hydrograph represents a 5-year event on Kuiu Island and all other storm hydrographs are proportional to this shape.
2) Inflow hydrograph is approximately linear over the time step.
3) Broad-crested weir equation is appropriate for modeling beaver dams
4) Beaver dam consists of a series of rectangular broad-crested weirs.
5) Weir discharge coefficient (C) for a smooth weir are applicable for determining discharge over a beaver dam (Table 6).
6) Pond water leaking through the dam is not important during storm events.
7) Beavers typically maintain full pond elevations.

Table 6. Broad-crested weir discharge coefficients (C) from King and Brater, (1963).

Head		Routing Coefficient	
Meter	Feet	8 ft weir length	16 ft weir length
0.15	0.5	3.22	3.22
0.30	1.0	3.30	3.44
0.46	1.5	3.32	3.46
0.61	2.0	3.36	3.42
0.76	2.5	3.40	3.41

8) Modified Puls methods is appropriate for modeling beaver ponds

RESULTS and DISCUSSION

According to U.S. Forest Service personnel on Kuiu Island, the annual precipitation for Southeast Alaska was about 20 to 30 percent below average for the period field data was collected (August, 1989). Hence, streamflows and pond volumes on Kuiu Island were correspondingly low. As described in the Methods section, water levels in ponds were mathematically "filled" to simulate winter storage conditions for pond routing.

Pond Ontogeny

Pond ontogeny may be an important factor affecting the response of beaver ponds to storm events. The increased volume of sediment stored within the pond increase with time. This additional sediment will change the stage-storage relationship. Decreases in water storage decreases the potential reduction in peak flows. Pond roughness will also increases depth decreases and vegetation invades the pond. Furthermore, changes in storage capacity by the addition of large quantities of wood deposits may also modify the hydrologic response of a pond. Large volumes of wood located in ponds may decrease pond storage available for affecting a storm hydrograph. Theoretically, as the pond ages the percentage reduction should decrease as the total pond volume decreases.

Log volumes were calculated assuming that the average length of logs in the pond were the same as log lengths for dam anchors and with no taper over the entire log length. Actual pond wood volumes are probably lower than these estimates due to taper along the length of the log. The average number of down-logs per pond was 9.5 and ranged from 0 to 38 (total number = 416). Standing dead or living trees within beaver ponds averaged 11.4 trees per pond and ranged from 0 to 56 trees per pond (total number = 501). Data analysis indicated that beaver ponds on Kuiu Island averaged only 18.6 m^3 of down-log wood volume; wood volumes ranged from 0 to 85 m^3.

Wood within beaver ponds is not likely a factor influencing the reduction of storm peak flows. Wood volumes averaged only 1.8% and 1.5% of the average summer- and winter-stage pond volumes, respectively. Furthermore, the maximum wood volume measured on Kuiu Island was only 8.3% and 6.8% of the average summer- and winter-stage pond volumes, respectively. Alteration of the stage-storage relationship due to woody debris input is probably very small and does not affect pond routing.

Dam Characteristics

Dam Anchors

A beaver's ability to utilize available riparian vegetation in dam construction is a trait that is not well understood. One of the possible reasons for the variable longevity of dams is the durability of large structural elements (dam anchors) that are often buried or incorporated into the dam.

Standing trees (bole and/or rootwad) and down-logs were the primary structural elements used by beavers on Kuiu Island. Determination of tree species and diameter were undertaken to characterize anchor properties that beavers consider acceptable for dam construction. However, many anchors could not be detected or measured once dam construction concealed the anchor's presence.

Field measurements indicate there were three standing tree species commonly incorporated into dams, the most common being Sitka spruce (Table 7). Standing dead or living trees averaged 3.1 per dam and ranged from 0 to 13 trees per dam (total number = 138). The average DBH for standing dead or living trees was 0.44 m with a standard deviation (SD) of 0.27 m (Figure 6).

Down-logs averaged 2 per dam and ranged from 0 to 10 logs per dam. The average down-log large-end diameter was 0.39 m (SD = 0.19 m). Down-logs averaged 14.1 m in length

Table 7. Number and percentage of standing trees species occurring as dam anchors on Kuiu Island, Alaska. (Number of dams = 44)

Species	Number	Frequency(%)	DBH (m)
Sitka Spruce	57	41.1	0.52
Red Alder	20	14.6	0.39
Western Hemlock	18	13.1	0.19
Alaska Cedar	6	4.4	0.34
Unknown	36	26.3	0.43
	N = 137	TOTAL = 99.9%	

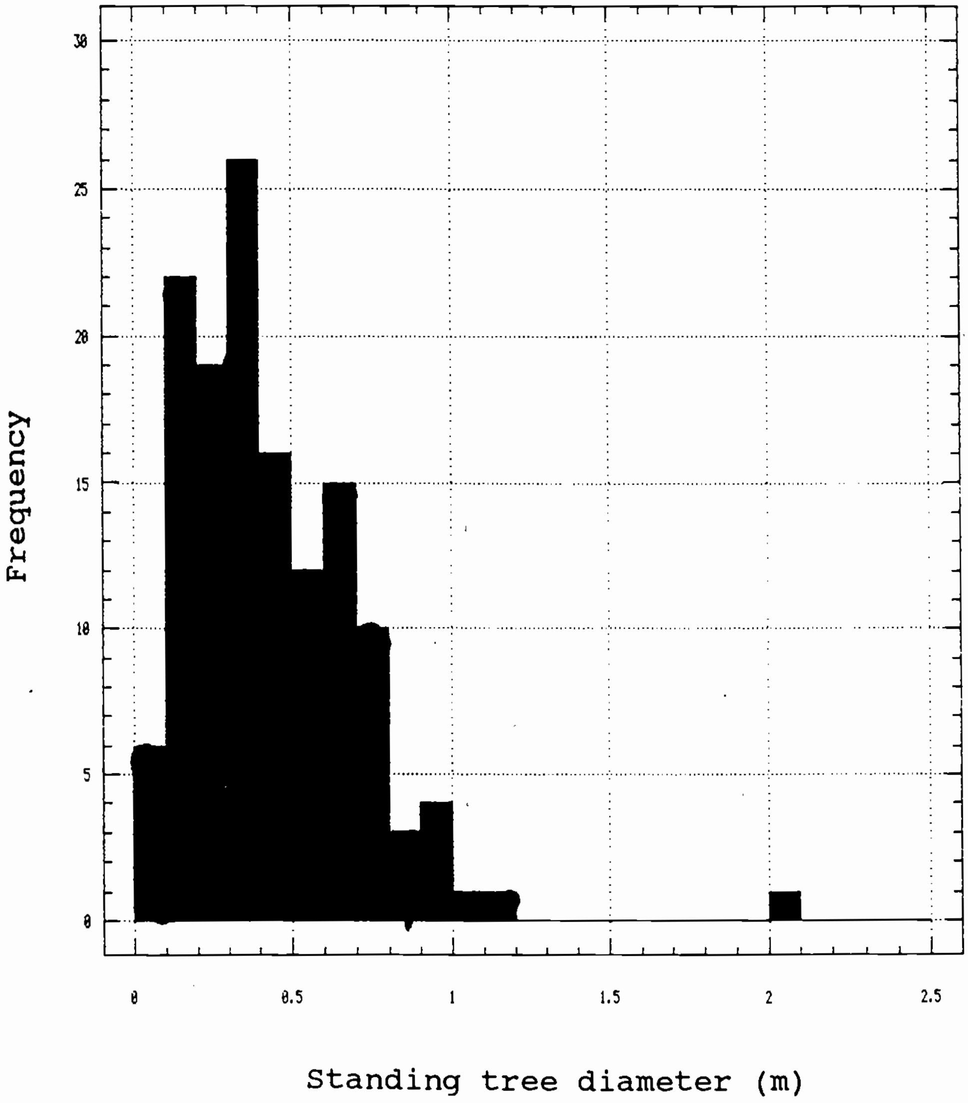


Figure 6. Frequency distribution of standing tree dam anchor diameters of beaver dams on Kuiu Island, Alaska (n = 137).

with a range of 1.0 to 35 m. This average was 44 percent of the average dam length. Log lengths tended towards a log-normal distribution (Figure 7). The average number of anchors per dam (standing trees plus down-logs) represented by the previous numbers provides a conservative estimate because of the unknown number of down-logs concealed within dams.

Dam "blow-outs" occur whenever the hydrostatic pressure on the dam exceeds the cohesive strength between the dam and the underlying soil or of the dam material. Smith (1950) concluded that log jams or large dam supports (dam anchors) prevent dams from washing out during storm events. Field observations from Kuiu Island may support this conclusion. Dam anchors provide additional resistance to the increased hydrostatic pressure associated with higher pond levels. Dams with large, sturdy anchors may have a lower failure rate, therefore providing better predator protection and overall beaver habitat. Recent studies of woody debris in streams suggests that the best stability may occur when log lengths equal or exceed stream bankfull width (Gillilan, 1989).

The use of dam anchors by beavers may depend upon a couple factors: (1) the presence of available materials, and (2) if the materials are present, the sizes and species are appropriate for use in dam construction. The location of anchor sites along a dam were not recorded, however,

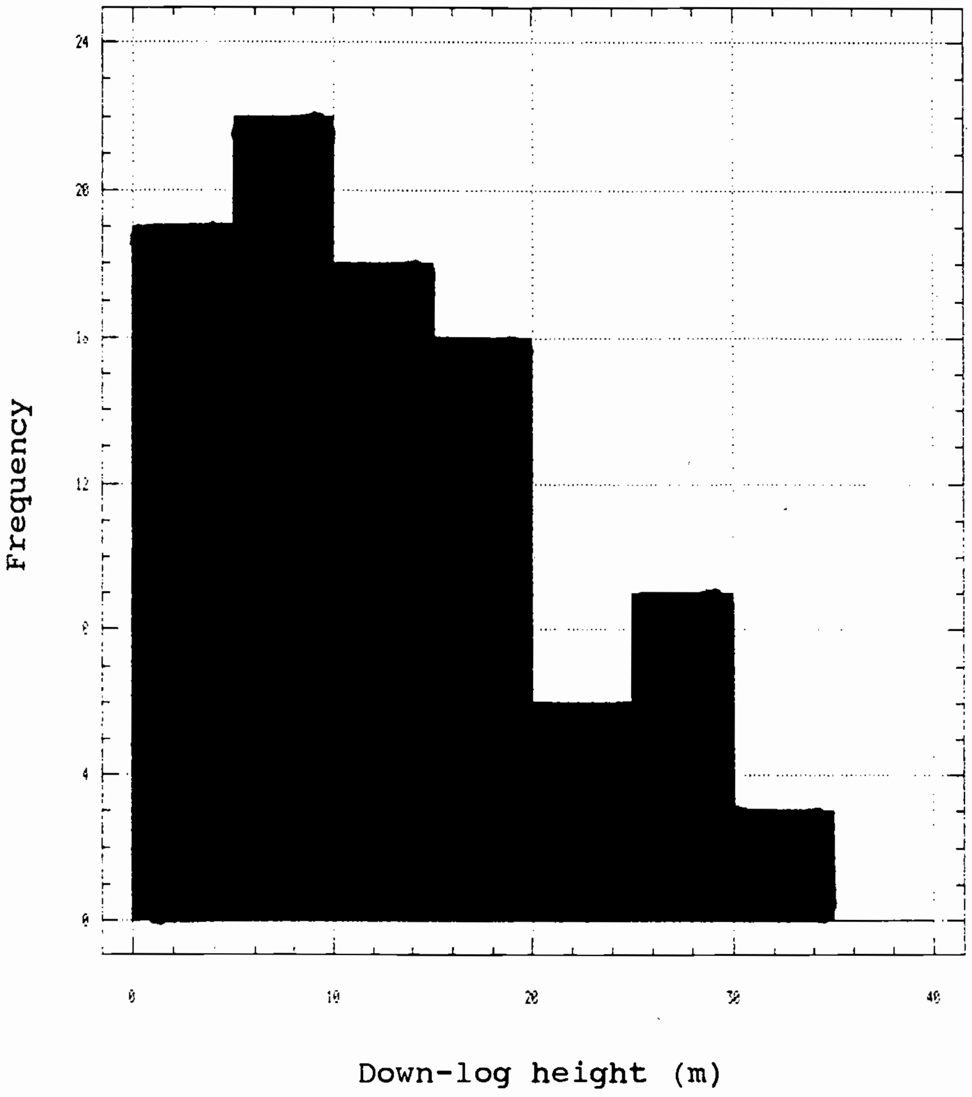


Figure 7. Frequency distribution of down-log dam anchor lengths on Kuiu Island, Alaska (n = 416).

field observations indicated that their location appeared random. It is not know whether beavers on Kuiu Island select dam sites because of the presence of anchors or select sites (which include anchors) for other reasons.

Windthrow was not a common occurrence for trees used as dam anchors. Trees associated with dams generally appeared to decay standing due to the roots zone becoming saturated, retarding decay. This process produces a short standing bole and rootwad which remains for many years and may provide long-term dam stability. Anchors situated above the stream or pond water surfaces may loose their structural integrity faster, providing less stability. Decay rates also vary depending on climate, anchor diameter, and species.

Dam Dimensions

Field observations indicated that each beaver dam was a relatively unique structure that occurs somewhat independently of the physical characteristics of adjacent sites or major watershed features. Beaver activities may be more closely associated with food availability, local hydraulics, and/or local geomorphology.

The average dam length was 32 m (Table 8). The estimated standard error was calculated to measure the precision of the mean (estimated point). The precision of the point estimation decreases as the estimated standard

Table 8. Descriptive statistics of beaver dam dimensions on Kuiu Island, Alaska (N = 44).

Statistic	Mean	Standard Deviation	Estimated Standard Error	Range
Length	32	27.3	4.1	2 - 132
Average Height	0.7	0.4	0.05	0.5 - 1.5
Average Base Width	2.5	0.8	0.1	1.0 - 4.5

error values increase. Dam lengths ranged from 2 to 132 m, a majority of the dams (55%) had lengths between 10 and 30 m (Figure 8). Regression analysis on dam length and valley width (natural logarithm transformed to adjust for unequal variance) indicated that dam length was significantly (p=0.05) related to valley width (r^2 of 0.099).

The average dam height was 0.68 m (SD = 0.35) and ranged from 0.05 to 1.5 m (Figure 9). Dam base width averaged 2.5 m (SD = 0.84) and ranged from 1 to 4.5 m. Both height and width generally appeared to fit a normal distribution.

All of the streams studied on Kuiu Island, with beaver dams, had gradients of three percent or less. A linear relationship between dam length and stream gradient was significant (P = 0.05) and had a r^2 of 0.29. However, disregarding the three dam lengths above 100 m (106, 111, and 132 m) the regression slope changed from positive to negative and became insignificant (r^2 of 0.071).

Scattergrams of dam height suggested a positive relationship with valley width and a negative relationship with stream gradient. There may also be a tendency for dam width to decrease as valley width increases. With the exception of Bryant (1984), researchers seldom indicate the methodology for measuring dam heights. Thus, comparisons of dam heights from various studies are difficult.

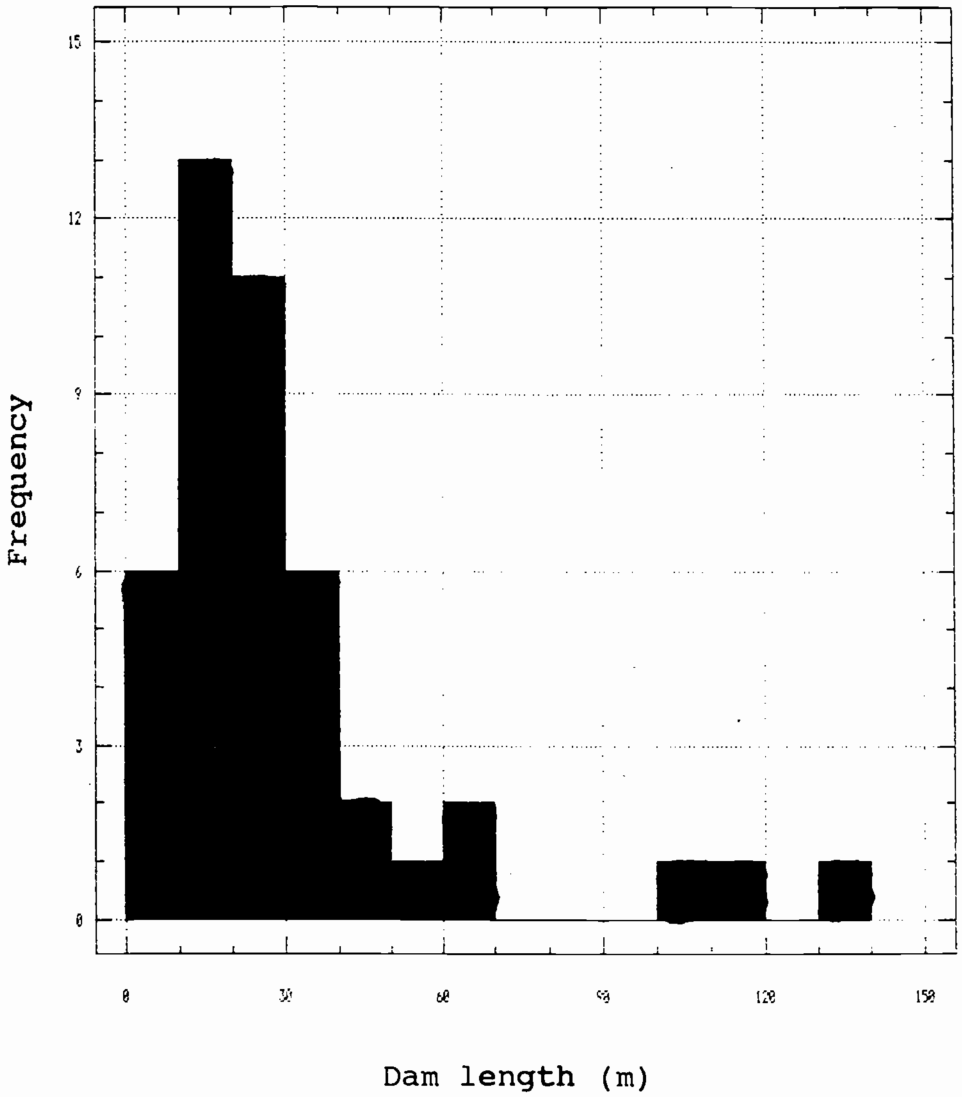


Figure 8. Frequency distribution of dam lengths, Kuiu Island, Alaska (n = 44).

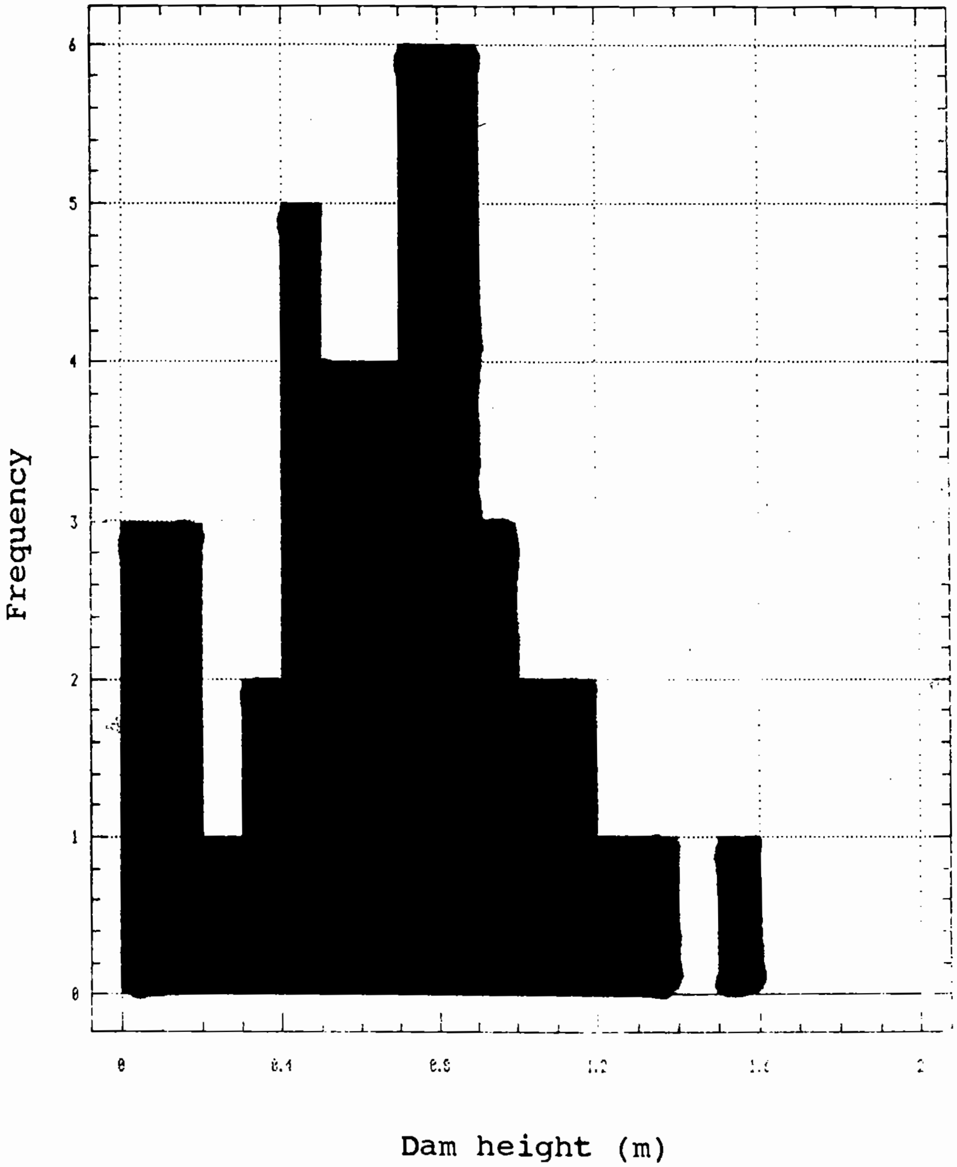


Figure 9. Frequency distribution of average dam heights, Kuiu Island, Alaska (n = 44).

Although study sites were selected to sample a variety of dam and pond types, field observations suggest that specific geomorphic conditions may exist more frequently that other. Sites were the dam length was constricted by the valley walls may have be more common than unconstricted locations. The number of constricted sites was not excepted by the author due to the broad U-shaped valleys on Kuiu Island.

Local floodplain morphology, channel type, and water overflow pattern may be the primary factors affecting the exact size and shape of beaver dams. Where dam anchors are utilized, the species and size of the anchor in conjunction with other construction material may also be factors. The interaction of all these factors may control the size and shape of beaver dams and ponds, which in turn determine the stage-storage and stage-discharge relationships.

The average dam length on Kuiu Island (32 m) was longer than most reported averages (Table 1). The reported averages of 13 to 28 m ranged from 41% to 87.5% of the Kuiu Island average. Dugmore (1914) reported an individual dam length of 152 m. This is 15% longer than the largest beaver dam on Kuiu Island (132 m). However, in general the dam lengths found on Kuiu Island were similar to those reported in Alaskan locations (Table 1). The average dam length reported by Bryant (1983) was 75% of the Kuiu Island average.

Incised streams in Southeast Alaska may have resulted in the generally longer dam lengths found on Kuiu Island. New dam construction first obstructs the incised stream channel, then spreads over the flat broad floodplain to maintain pond elevations.

The average dam height of 0.68 m was lower than most averages reported in the literature (Table 1), however, this average was within the ranges reported. Reported dam heights ranged from 44% of the Kuiu Island average height to 224% of this average. For example, the average dam height on Blind Slough, Alaska (Bryant, 1983) was 47% higher than the average on Kuiu Island. The only lower average was on Long Creek, Oregon where the average height (0.55 m) was 81% of the Kuiu Island average height (Bruner, 1989).

Analysis of the field data suggested a logarithmic relationship between dam heights and lengths. A reciprocal model [$\log(1/Y) = -32.1 + \log(x)(9.1)$] was used to described the relationship between dam height (Y, in meters) and length (X, in meters). This relationship was statistically significant ($P = 0.05$) with a r^2 of 0.12. Base width appears to be a function of beaver activities that maintain pond elevation and was not significantly related to other dam or watershed features.

Differences in dam dimensions may be due to measuring techniques or the valley morphologies associated with different study areas. Although regional averages for dimensional characteristics of beaver dams may exist, limited data from Kuiu Island and existing literature does not allow for a definitive conclusion.

Dam Construction

During field studies, two dams were discovered in the early phases of construction. The stream reach consisted of a 1.0 m high bank along the outside of a bend and a gravel/sand bar along the inside bend. Gravel sized material made up the streambed whereas stream banks and floodplain terraces consisted of fines and interlayered sands.

Beavers selected gradient breaks at the tail of riffles where the water was the shallowest for both sites. Rocks, woody debris, and mixed accumulation of these material were used to form a line across the stream to reduce the flow velocities. Branches were added perpendicular to the barrier to form the dam base. Additional branches and sticks were placed on top of this layer to increase dam height.

There appeared to be no attempt to weave new and old material together. Additional heavy material (rocks and pieces of large organic debris) were used to hold the branches in place. These objects were always placed parallel to the localized flow. As the stream moved around the end of a dam, new material was placed parallel to this flow. This may explain the curved shape of many dams. During early stages of construction there was no evidence that beavers used streambed fines to seal a dam. This was likely due to the absence of such material within this reach. Fine organics (leaves) from trees felled by beavers sealed the dam face over time. Once ponds accumulate sediment, beavers may use this material to reduce or prevent water leakage from the pond.

McComb, Sedell, and Buchholz (1990) reported that beavers do not select sites that have bedrock stream beds. Field observations support this conclusion. However, beavers did use cobble sized material as a source of dam materials. The vertical banks caused by local bank erosion or stream incision appears to be suited for beaver construction. Vertical banks may provide an anchor point and maximize change in pond volume with the least amount of building materials. An additional benefit of building in an incised channel may occur during high flow events. During storm events, flood water will be dispersed over a floodplain, hence minimizing the range of hydrostatic pressures experienced by a dam.

Pond Dimensions

Beaver ponds may greatly increase the volume of water stored on a watershed compared to similar free flowing reaches that do not have beaver ponds. Thus, altering the volume of stored water and the hydrograph timing within a watershed may change the hydrologic response at the outlet of the watershed.

Pond dimensions found on Kuiu Island were highly variable. Furthermore, summer-stage (water elevation existing during summertime measurements) and winter-stage (water elevation equal to the lowest point on the dam) conditions were sometimes drastically different.

Only 13 ponds (30%) had water levels equivalent with winter-stage elevations when field data was collected in August of 1989. The average vertical difference in pond levels (i.e., from the lowest elevation along the top of the dam to the level of the water in the pond) was 0.2 m; 22 of the ponds (50%) had elevational differences of 0.25 m or less. The maximum elevation difference between dam and pond stage was 0.6 m.

Surface area for summer-stage conditions averaged 1700 m^2 (SD = 2760 m^2), but 33 ponds (75%) had surface areas of 1833 m^2 or less (Figure 10). The average winter-stage pond surface area was 2140 m^2 (SD = 3200 m^2) and ranged from 35

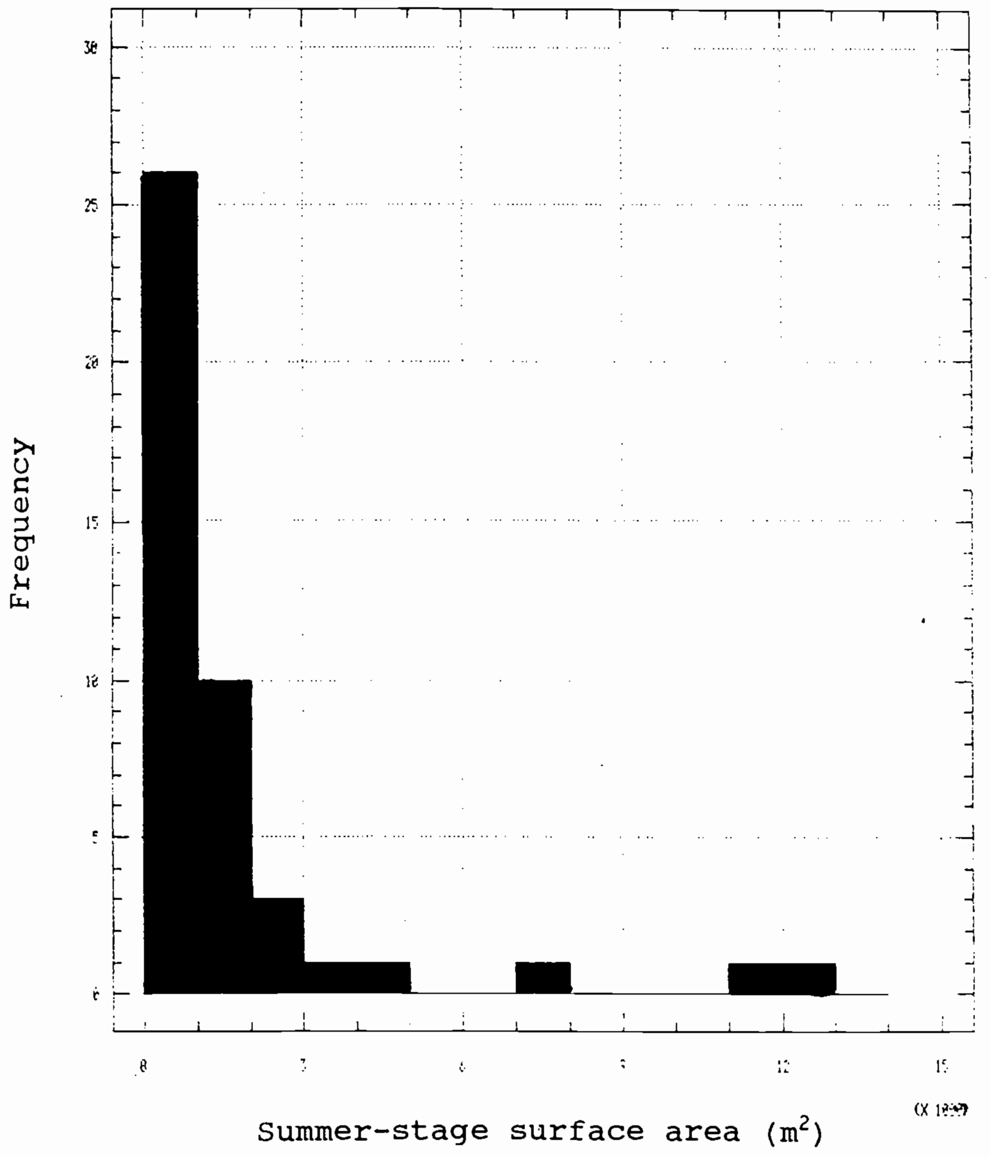


Figure 10. Frequency distribution of summer-stage pond surface areas on Kuiu Island, Alaska (n = 44).

to 13930 m^2. In this situation, 75% of the ponds had surface areas of 1912 m^2 or less.

The average summer-stage pond volume on Kuiu Island was 1020 m^3 (SD = 2060 m^3). A Chi-square test indicated that the frequency of pond volumes, which ranged from 10 to 11400 m^3, appears to fit a log-normal distribution (Figure 11). The average winter-stage pond volume was 1250 m^3 (SD = 2470 m^3) and ranged from 15 to 13290 m^3. Thirty-three ponds (75%) had volumes of 988 m^3 or less. The data indicated that beaver ponds can create a considerable amount of slack water habitat that would not normally be present along stream systems.

The average summer-stage pond volume was 37 times greater than the volume of water in adjacent unponded stream channels. These pond/channel volume ratios ranged from 1 to 121. However, 75% of the ponds had ratios of 49 or less. The site with the largest ratio of pond-to-channel volume consisted of an unconstrained dam and pond, however, this geomorphic control condition was also true for the site with the minimum pond-to-channel volume ratio.

Surface areas differences between summer- and winter-stage conditions averaged 427 m^2 and ranged from 0 to 7032 m^2 (Figure 12). Volume differences between the two stage conditions averaged 230 m^3 and ranged from 0 to 3987 m^3. This is a 25% and 25.5% increase in the average summer-

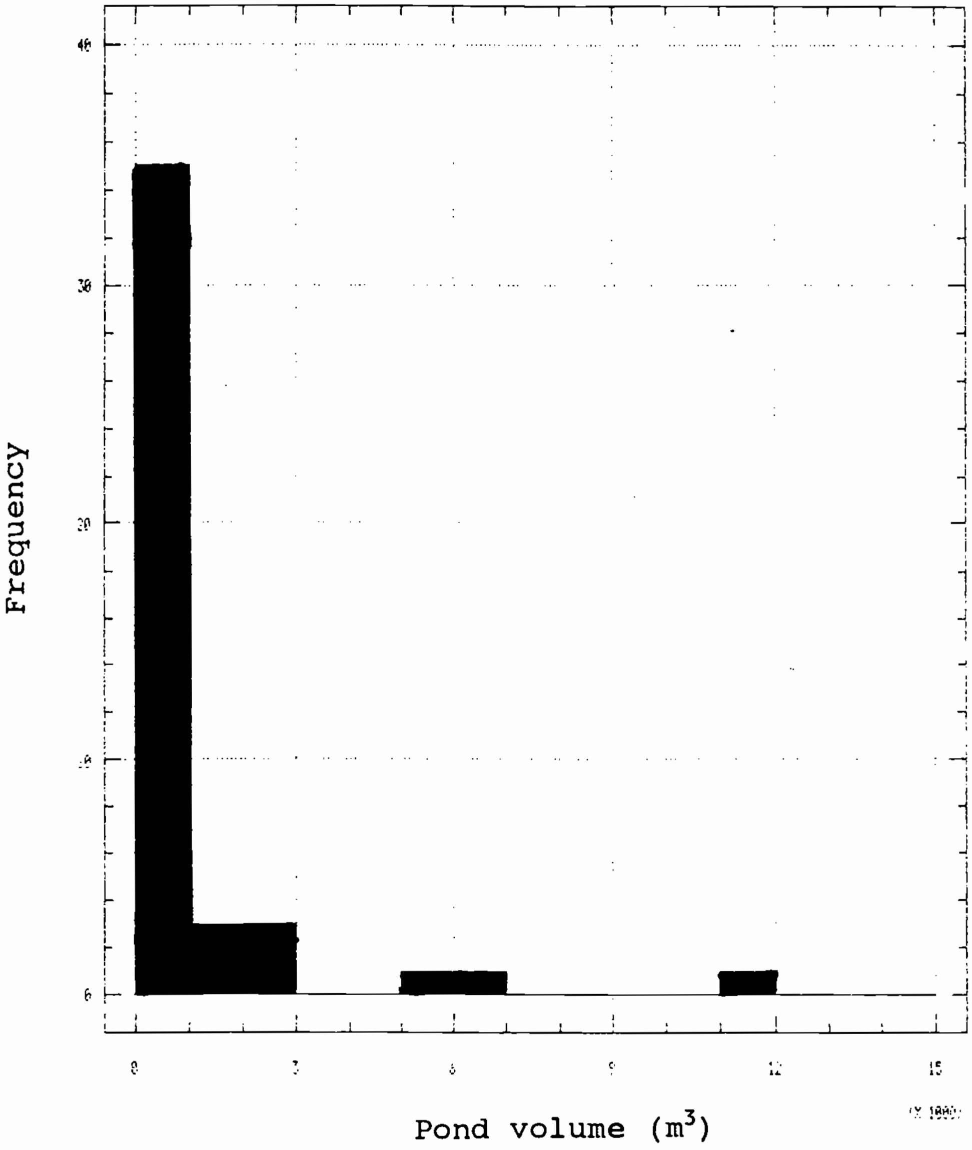


Figure 11. Frequency distribution of summer-stage pond volumes, Kuiu Island, Alaska (n = 44).

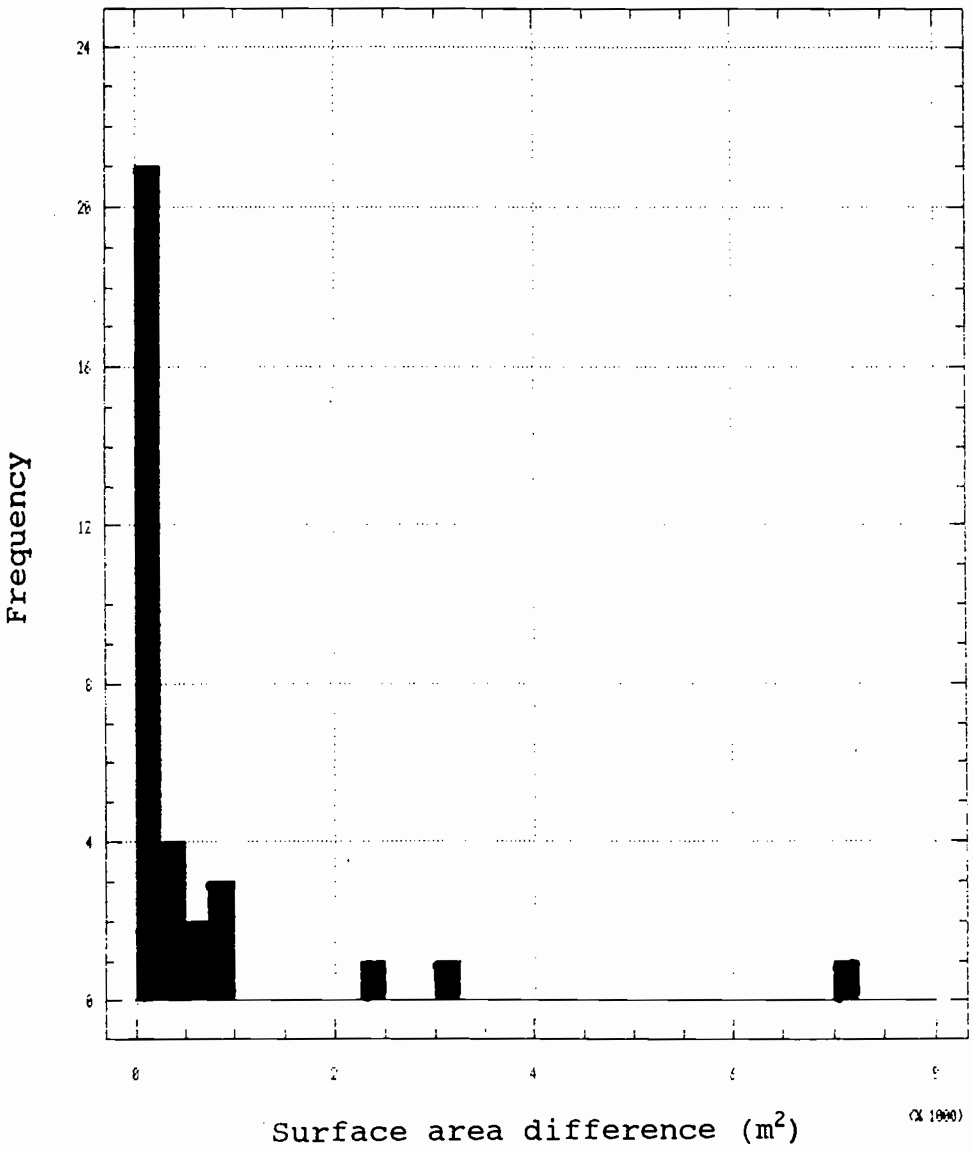


Figure 12. Frequency distribution of pond surface area differences between summer- and winter-stage conditions on Kuiu Island, Alaska (n = 44).

stage pond surface area and volume, respectively. Seventy-five percent of the ponds had volume differences of 226 m^3 or less (Figure 13).

Pond length measurements represent the distance from the crest of the dam to the farthest influences of the pond. On Kuiu Island, summer-stage pond length averaged 60.7 m (SD = 45.1 m) and ranged from 7 to 195 m (Table 9). Seventy-five percent of the ponds had lengths of 78 m or less (Figure 14).

Two ways were used to describe pond depths; average and maximum pond depth. Average pond depth was defined as the total volume divided by the total surface area. The mean summer-stage average depths were 0.5 m with a SD of 0.2 m (Table 10). The summer-stage maximum pond depths averaged 1.2 m and ranged from 0.6 to 2.1 m. Winter-stage indicate the highest correlation for dam or pond dimensions was between pond surface area and volume. For summer-stage conditions, pond volume was significantly related to pond surface area with a r^2 of 0.90 (Table 11). The r^2 for the winter-stage condition was 0.91. Except for the equations illustrated in Table 11, most other regression equations were nonsignificant for pond dimensions versus dam or watershed characteristics.

Field observations suggest beaver ponds are formed by interactions between dam height, stream type, stream gradient, and valley features. Local stream and watershed

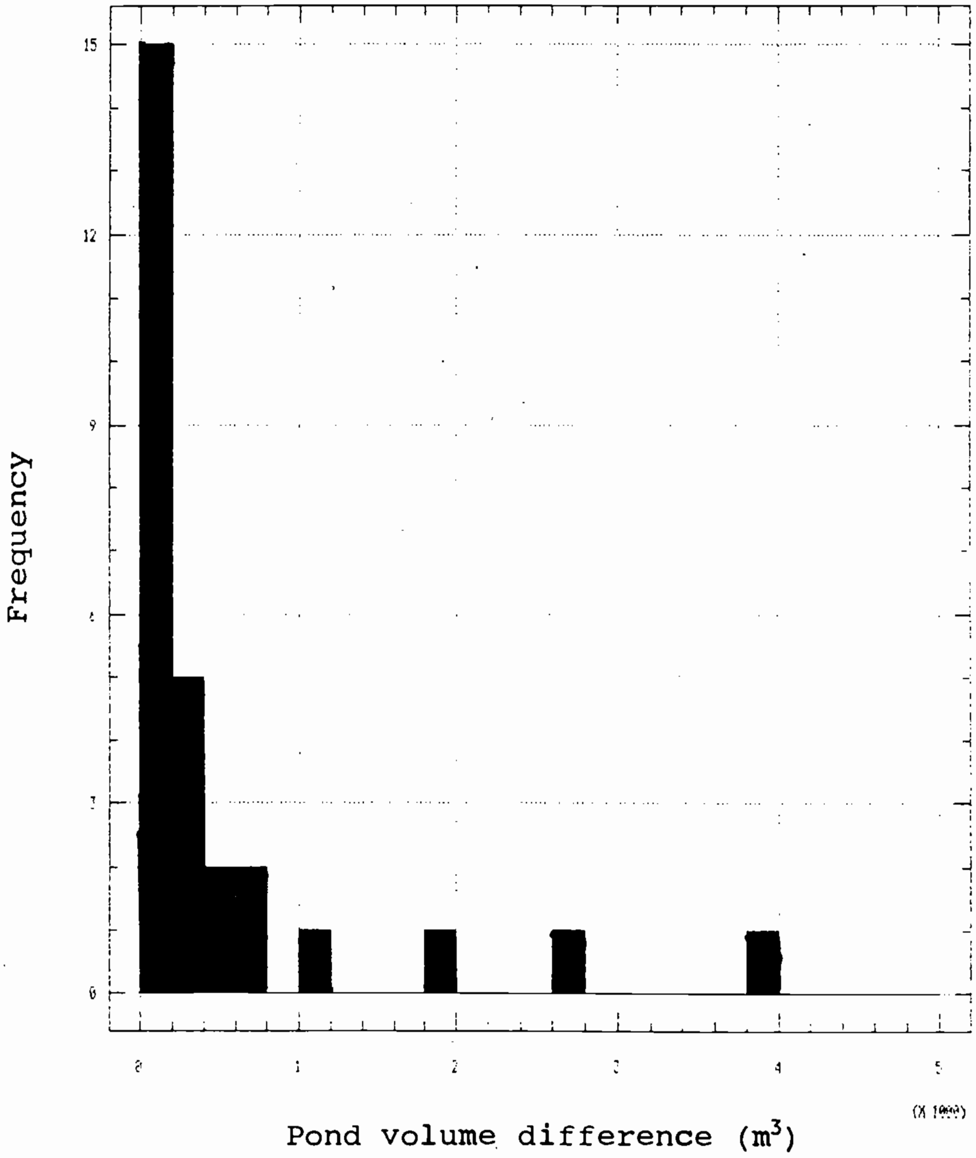


Figure 13. Frequency distribution of pond volume differences between summer- and winter-stage conditions on Kuiu Island, Alaska (n = 44).

Table 9. Descriptive statistics of beaver pond dimensions during summer-stage conditions on Kuiu Island, Alaska (N = 44).

Statistic	Mean	Standard Deviation	Estimated Standard Error	Range
Volume (m^3)	1,020	2,060	311	10 - 11,400
Surface Area (m^2)	1,700	2,760	416	32 - 13,000
Length (m)	60.7	45	6.8	7 - 195
Average Depth (m)**	0.5	0.2	0.03	0.1 - 0.9
Maximum Depth (m)	1.2	0.3	0.05	0.6 - 2.1
Ratio*+	37	35	6.5	1 - 121

** Pond volume divided by surface area

* Pond volume divided by channel volume

\+ N = 29

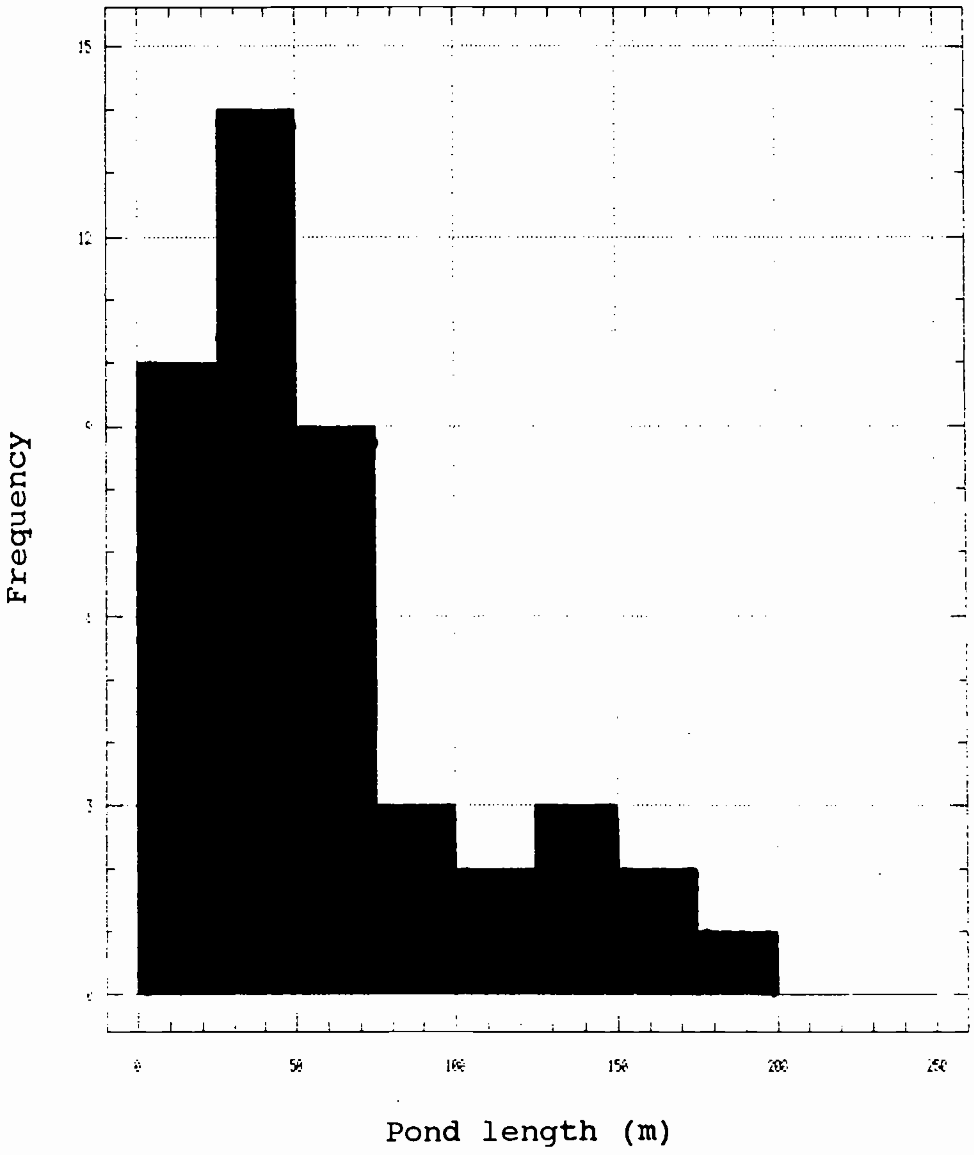


Figure 14. Frequency distribution of summer- and winter-stage pond lengths, Kuiu Island, Alaska (n = 44).

Table 10. Descriptive statistics of beaver pond dimensions during winter-stage conditions on Kuiu Island, Alaska (N = 44).

Statistic	Mean	Standard Deviation	Estimated Standard Error	Range
Volume (m^3)	1,250	2,470	373	15 - 13,290
Surface Area (m^2)	2,140	3,200	482	35 - 13,970
Average Depth (m)**	0.5	0.2	0.03	0.1 - 1.4
Maximum Depth (m)	1.4	0.4	0.1	0.7 - 2.5
Ratio*+	50	41	7.6	1 - 164

** Pond volume divided by surface area
* Pond volume divided by channel volume
\+ N = 29

Table 11. Regression analysis on dam and pond characteristics on Kuiu Island, Alaska. (N = 44)

Regression Equation	r^2	Significance[a]
$\ln(Y) = -1.11 + (1.05)\ln(X)$ X = summer-stage pond surface area (m^2) Y = summer-stage pond volume (m^3)	0.90	YES
$\ln(Y) = -1.21 + (1.07)\ln(X)$ X = winter-stage pond surface area (m^2) Y = winter-stage pond volume (m^3)	0.91	YES
$Y = 28.3 + 1.02(X)$ X = dam length (m) Y = pond length (m)	0.38	YES
$Y = 0.04 + 1.51(X)$ X = dam length (m) Y = summer-low stage pond volume (m^3)	0.64	YES
$Y = 2.4 + 1.32(X)$ X = dam length (m) Y = summer-stage pond surface area (m^2)	0.63	YES
$\ln(Y) = 1.20 + \ln(X)(1.47)$ X = dam length (m) Y = winter-stage pond surface area (m^2)	0.72	YES

[a] "YES" denotes significant at 0.05

features have the greatest influence on the resulting pond dimensions. Beavers seem unlikely to construct a specific type of pond, but rather the largest possible.

Pond length, as measured, on Kuiu Island was not a reliable measurement for determining the extent beavers can influence streams. Generally beaver ponds in low gradient channels extended to the next upstream dam, hence pond length did not change as pond volume increased. The presence of an upstream dam site generally limited pond length, not the height of the downstream dams.

The average summer-stage surface area of 1700 m^2 was 3 to 10 times larger than other published averages, except for beaver ponds reported in Alaska (Table 2). Pond comparisons within Alaska becomes much less clear. Sanner (1987), in the Kenai Mountain of Alaska, reported an average surface area of 7400 m^2, which was 4.4 times greater than Kuiu Island average. However, the average maximum depth for Kuiu Island was only 8% greater than the average maximum depths found by Bryant (1983), which was in a mountainous region.

The average summer-stage volume of 1020 m^3 was generally higher than other averages reported in the literature (Table 2). Again, this may be due to the different valley types associated with various study areas. The average Kuiu Island summer-stage pond volume was 4 to 13 times greater than other averages reported in the literature. The summer-stage pond volumes in Washington were 88% of the Kuiu Island summer-stage average, however, the fall volume was 2.5 times greater than the Kuiu Island winter-stage average (Scheffer, 1938). As mentioned above, the lack of data from Kuiu Island and the literature made comparisons difficult.

Pond Routing

The below average rainfall conditions encountered during summer field measurements required extrapolation of pond dimensions to the winter-stage conditions using side-slope and depth transect information, since pond dimensions measured during summer-stage did not represent conditions expected during peak flow events. Only the winter-stage conditions were used for pond routing.

A range of storm magnitudes were selected to evaluate the effect of beaver ponds on peak discharge, during winter-stage conditions. Watershed size and return interval are directly related to the magnitude of peak discharge. As the storm flow increases, any reduction in the peak flow caused by an individual beaver pond should theoretically decrease.

Peak flow reductions occur when inflows are temporarily stored (i.e., detained) in beaver ponds before being released downstream. Increasing the detention storage for a particular pond, increases the expected reduction in peak flows. During a high flow event, maximum pond volume occurs when the inflow and outflow rates are equal.

Crest profiles of beaver dams on Kuiu Island had relatively flat surfaces. Elevational differences between the highest and lowest points along the crest of the dams used for pond routing (sites #5 and #9) were 0.13 and 0.03 m, respectively. The long outflow surface, per total dam length, resulted in very little additional storage producing high volumes of discharge. The flat profiles also resulted in stage-discharge and stage-storage relationships with very steep slopes (Figure 15 and 16).

A medium- (site #5) and large-sized (site #9) beaver pond were selected to determine the theoretical average and maximum reduction in peak flows. These ponds were represent the 50 and 90 percentile of pond surface area, respectively.

The outflow hydrograph shape always had the same triangular shape as the inflow hydrograph (Figure 17). The lack of detained storm water resulted in small changes in time-to-peak. Regardless of the inflow hydrograph the time-to-peak did not change by more the 10 minutes. Modeling simulations calculated outflow values only 30 minutes after the end of the inflow hydrograph. This was

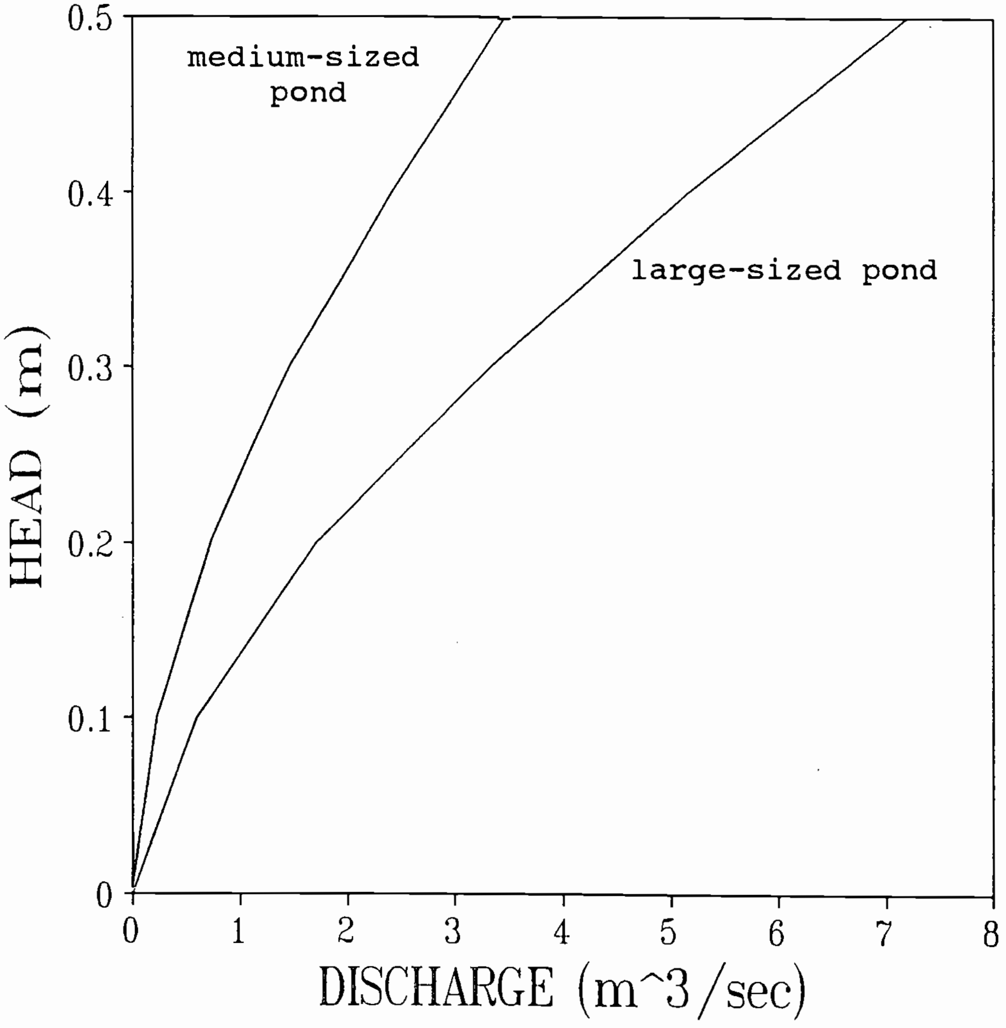


Figure 15. Stage-discharge relationships for medium- and large-sized ponds on Kuiu Island, Alaska. (A head of "0" represents a full pond.)

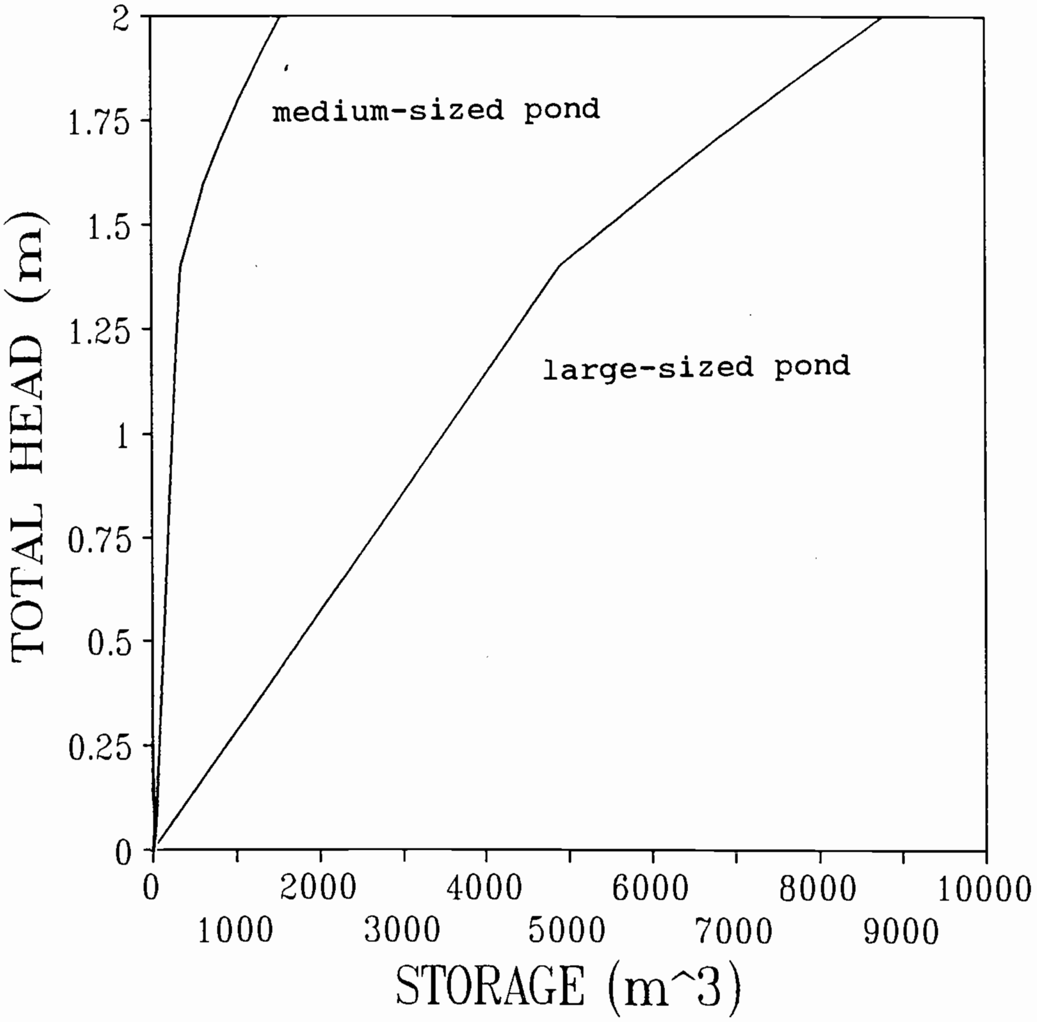


Figure 16. Stage-storage relationships for medium- and large-sized ponds on Kuiu Island, Alaska. (A head of "0" represents a full pond.)

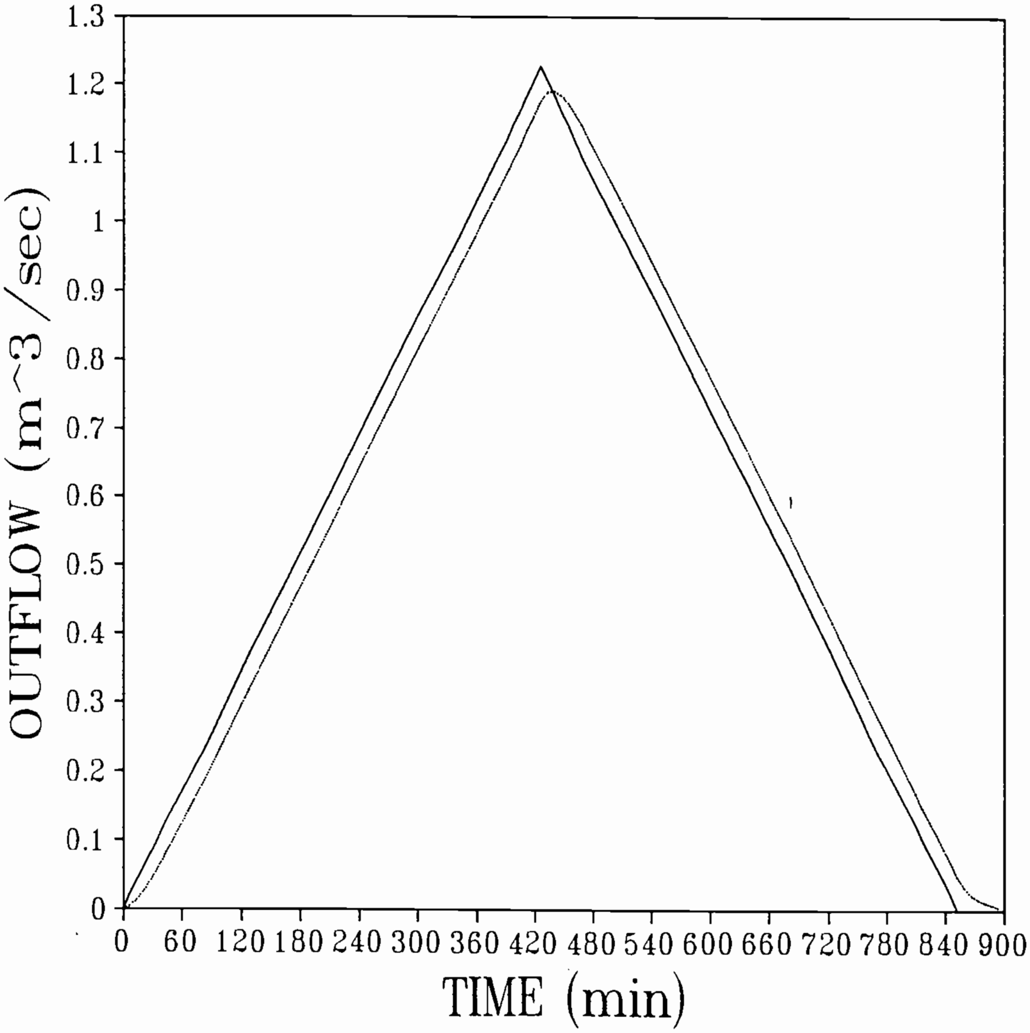


Figure 17. A 50-year storm event inflow and outflow hydrographs for a large-sized (6002 m^2) pond in a watershed 10 times large than the pond.

generally sufficient to determine end of the outflow hydrograph.

Modeled peak flow reductions for single beaver ponds were small (i.e., 1 - 5%) regardless of watershed area, return interval or size of the beaver pond. The medium-sized pond (site #5) reduced peak flows by 0.85% to 3.8% (Table 12). The large-sized pond (site #9) reduced peak flows by 1.4% to 5.3% (Table 13). The size of the beaver pond in relation to the size of the inflow hydrograph determined the percentage reduction in peak flows. For each pond, the minimum peak flow reduction occurred for the 50-year events with the largest watershed size. The maximum peak flow reduction occurred during the 2-year return interval with the smallest watershed size.

Reductions in peak flows became increasingly important when storm events were simulated to pass through a series of ponds. Hydrograph peaks were slightly reduced after each pond resulting in an cumulative reduction for each successive pond (Figure 18). A series of ponds had similar responses in time-to-peak and hydrograph shape as single ponds (i.e., smaller storms had greater reductions than larger flows). Five medium-sized ponds (site #5) in a series for the 2-, 10-, and 50-year storm event had total reductions of 9.7%, 4.1%, and 1.9%, respectively (Table 14). The large-sized pond (site #9) after the fifth pond had total reductions of 14.0%, 8.8%, and 3.9% (Table 15).

Table 12. Theoretical percentage reduction in storm flow peak discharge by return interval and watershed area for a medium-sized pond (Site #5) on Kuiu Island, Alaska.

	Return Interval			
Watershed Area*	2-year	10-year	25-year	50-year
10	3.8	3.1	2.3	1.9
20	3.8	3.1	2.3	1.9
50	3.7	1.3	1.0	0.85
100	1.4	1.3	1.0	0.85
500	1.4	1.3	1.0	0.85
1000	1.4	1.3	1.0	0.85

* = Multiplication factor to determine watershed size from pond surface area

Table 13. Theoretical percentage reduction in storm flow peak discharge by return interval and watershed area for a large-sized pond (Site #9) on Kuiu Island, Alaska.

Watershed Area*	Return Interval			
	2-year	10-year	25-year	50-year
10	5.3	3.6	3.2	2.8
20	5.2	3.6	3.1	2.7
50	5.1	3.7	3.1	2.7
100	5.1	3.7	3.1	1.7
500	3.1	2.2	1.7	1.4
1000	3.0	2.2	1.7	1.4

* = Multiplication factor to determine watershed size from pond surface area

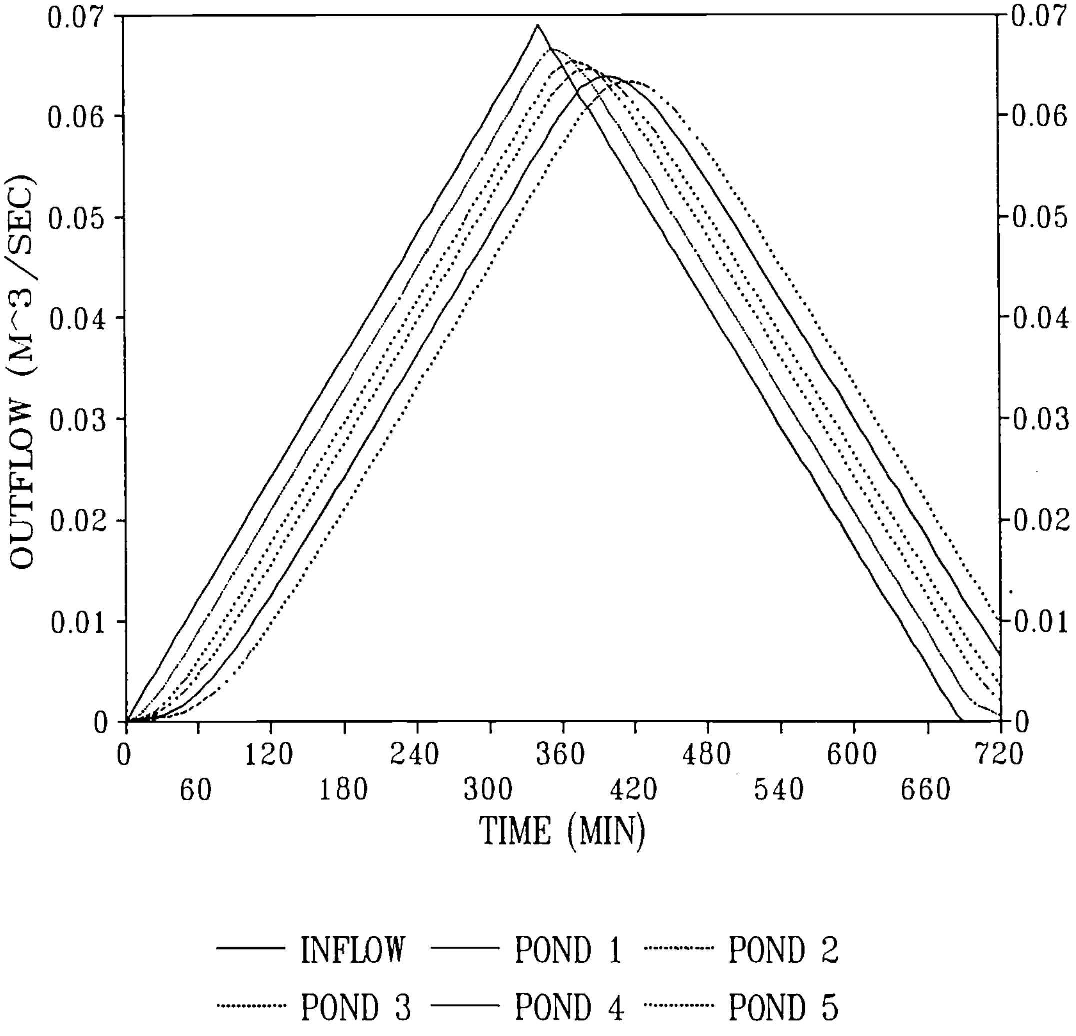


Figure 18. Inflow and outflow hydrographs for five large-sized ponds during a 10-year storm in the smallest watershed area, Kuiu Island, Alaska.

Table 14. Theoretical cumulative percentage reduction in peak discharge for a series of five medium-sized ponds (Site #5) on Kuiu Island, Alaska.

	Watershed size and Return interval		
Pond Number	10 X 2-year	50 X 10-year	1000 X 50-year
1	3.8	1.3	0.85
2	5.8	2.0	1.1
3	7.3	2.6	1.4
4	8.6	3.3	1.7
5	9.7	4.1	1.9

Table 15. Theoretical cumulative percentage reduction in peak discharge for a series of five large-sized ponds (Site #9) on Kuiu Island, Alaska.

Pond Number	Watershed size and Return interval		
	10 X 2-year	50 X 10-year	1000 X 50-year
1	5.3	3.7	1.4
2	8.2	5.4	2.3
3	10.5	6.8	2.9
4	12.4	7.9	3.4
5	14.0	8.8	3.9

The time-to-peak for ponds in series increased as the outflow peak broadened. The increased time-to-peak for each pond was again small, however, the cumulative effect on timing may be important.

The number of ponds in sequence required to obtain an important reduction in peak flows increased as the return period and watershed size increased. Again, the size of the beaver pond in relation to the size of the inflow hydrograph, plus the number of ponds in series, determined the magnitude of the peak flow reduction.

The flat surface profile of beaver dams was probably the principal factor for the small peak flow reductions. Increasing pond stage resulted in a large proportion of the dam discharging water downstream, thus preventing a large quantity of water from being stored behind the dam. The magnitude of the reduction is a function of the volume of water stored from the inflow hydrograph. Without this water being stored from the inflow hydrograph, there cannot be an effect on the outflow hydrograph. Flow reductions are related to antecedent conditions, inflow hydrograph shape, pond size in relation to storm size, and outlet structure configuration.

Besides hydrologic effects, the flat profile may be an important aspect in dam longevity. Beavers fill the lowest points along the dam to maintain or increase the pond levels. This behavior forms a uniform surface that creates a wide discharge structure. Hence, only small increases in pond head occurs during storm events, minimizing the increase in the hydrostatic pressure on the dam. Regardless of storm event size , pressures will remain relatively constant because the water level is only slightly higher than the pre-storm condition. This reduces the chances of dams blowing-out due to excessive hydrostatic pressures.

Standard engineering weir stage-discharge relationships assume an impervious dam structure. However, beaver dams discharge water through the structure. Discharge (leak) rate is likely a function of the head difference between the pond and stream elevations. Leak rate is probably not a hydrologic factor during storm events. Additional pond water from an inflow hydrograph is discharged quickly over the dam, preventing a large head increase over the normal pond level. Simultaneously, stream volumes increase during storm events decreasing the elevational difference between the pond and stream surfaces. The decreased head should theoretically result in a reduction of the leak rate. Leak rate calculations were not included during any of the routing simulations.

Pond water elevations below the lowest point along the dam crest should not affect the outflow hydrograph, depending on the storm hydrograph volume in relation to the existing pond volume. Beavers appear to maintain ponds surface elevations as high as possible to maximize available habitat. This results in a full ponds being the normal condition. Unusual conditions (dry weather, excessive dam leakage, etc) may cause surface elevations below the crest of the dam. This situation results in a portions of the inflow hydrograph (I_1) required to fill the pond, to the crest of the dam, before initiation of discharge. Once the pond fills to the crest of the dam, the outflow hydrograph will raise quickly and mirror the inflow hydrograph. The percentage reduction in peak flow is dependent on the volume of water from the inflow hydrograph required to fill the pond. Greater the percentage of the inflow hydrograph volume required to fill the pond the greater the percentage reduction in peak flow. For example, a 10% reduction in pond volume (large-sized pond) does not change the theoretical percentage reduction (3.7%) in peak flow for a 10-year storm event (Figure 19). However, a 50% reduction in pond volume (large-sized pond) also has a 3.7% theoretical reduction in peak flow for the same storm event (Figure 20). The exact reduction is a function of the inflow hydrograph volume and the pond volume below "full-pond" elevation.

Based on comments prevalent in the literature, beaver dams and ponds generally did not respond as expected to inflow hydrographs. Routing simulations indicated beaver dam and ponds did not substantially decrease peaks flows

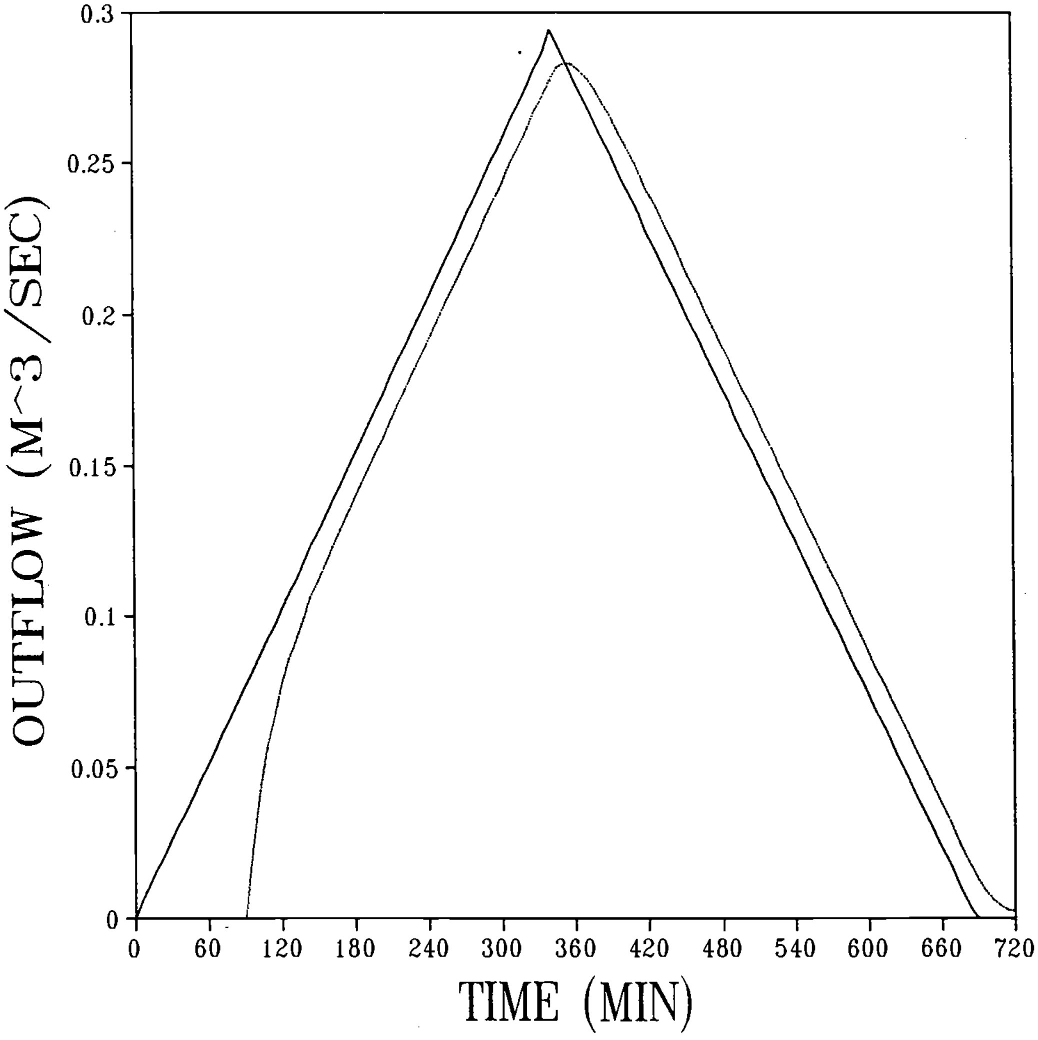


Figure 19. Inflow and outflow hydrographs for a large-sized pond during a 10-year storm (50X) with 5% of the inflow hydrograph volume required to fill pond.

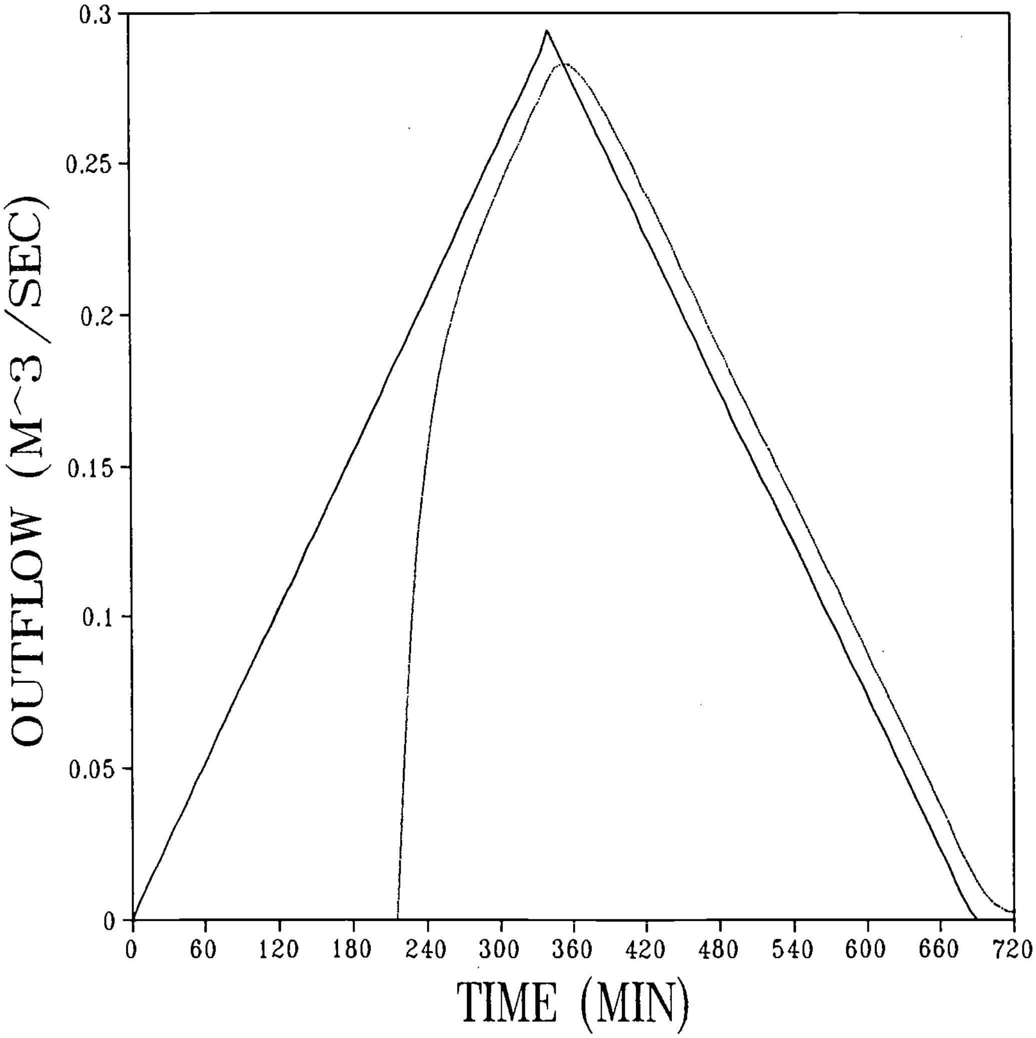


Figure 20. Inflow and outflow hydrographs for a large-sized pond during a 10-year storm (50X) with 50% of the inflow hydrograph volume required to fill pond.

(for any return interval or watershed area), delay timing of peak, or increase the hydrograph duration. As peak flows increase, either by watershed area or return interval, the magnitude of the reduction generally decreased. The medium-sized pond had a smaller reductions in peak flows and a narrower range of reductions. This may suggests that pond location within the watershed is not the most important factor. Ponds located at the very head of the watershed and encompassing most the drainage area would be an exception.

Beaver are still important hydrologically even with the lack of large reductions in peak flows. Large amount of sediment can be stored behind dams, improving the overall stream water quality. Sediment storage in low order tributaries can prevent damage to fisheries spawning and rearing areas. Trapping sediment from unstable hillslope areas or from management activities may be a major component in maintaining a productive stream environment. In landslide areas beaver pond may reduce the amount of material entering channels. Bedload storage within the pond may also have an important effect. Stream competence increases downstream of beaver dam due to bed material being stored in the pond may increase stream scour.

Collapse of beaver dams during storm events could greatly increase local flows if the dam break during the storm peak. The increased velocities and volumes may scour the stream channel bed and/or banks. Removal of dams can have a large effect of stream morphology. Beschta (1979) reported a lowering of the stream beds by as much as 2 m in the Oregon Coast Range after large organic debris was removed. This same process is likely to occur when beaver dams are removed.

Pond formation may be an important factor affecting the occurrence of in-channel large organic debris. Tree drownings within ponds may provide important allochthonous inputs to a nutrient-poor system. The slow decay of down-logs may also provide a long-term source of nutrients. These logs may produce in-channel pools and large quantities of escape and hiding cover for fish.

An important hydrologic benefit not evaluated in this study is the dispersion of storm water onto floodplain surfaces below a dam. Flat dam profiles discharge storm water over a relatively broad area, hence decreasing the amount of water discharged directly back into the channel. The relatively high substrate roughness reduces the flow velocities and thus, floodplain water is temporary stored (detention storage) before accumulating in downstream channels. This effect may cause an important reduction in peak discharge some distance below the dam. The magnitude of such a reduction is not known.

CONCLUSION

Beaver dams and ponds are highly variable components of the landscape that fulfill a wide variety of biologic and hydrologic functions. The potential for peak flow alteration represents only one of these functions.

Average dam and pond dimensions measured in this study were generally larger than other reported averages. However, comparisons between studies are difficult due to the lack of information. The larger than average dam and pond sizes on Kuiu Island were not just the result of the broad U-shaped valleys, but the localized geomorphology of the site. The general pond size and shape appear to be determined by the valley shape, however, the exact dimensions are determined by dam size in conjunction with local stream and floodplain morphology. Dam anchors are likely a major contributor to overall dam stability; increased size and number of anchors should decrease the probability of dam failures during high flows.

Dam construction behavior results in relatively flat dam crest profiles. This shape makes beaver dams very efficient at routing stormwater through a pond. Flat profiles are beneficial in preventing significant increases in pond elevations during high flow periods. Without large changes in the volume of water stored in a pond, peak flows can not be greatly affected. Primarily due to the efficient routing of outflows over a dam, ponds do not have a significant effect on peak flows. Medium- and large-sized beaver ponds theoretically reduce peak flows by about 3.8% and 5.3%, respectively. The magnitude of the reduction is a function of the beaver pond in relation to the size of the storm event. A series of five consecutive medium- and large-sized ponds reduce peak by 9.7% and 14.0%, respectively.

The magnitude of the reduction depends of the size of the pond, size of the storm, and number of ponds in series. Dams routing water onto the floodplain may increase detention storage and floodplain recharge, further influencing hydrologic response. A series of beaver ponds in combination with large floodplain storage might significantly reduce peak discharges.

The failure of beaver dams during storm events can possibly release a considerable volume of water downstream that may increase peak discharge. If the dam failure corresponds with the inflow hydrograph peak, the resulting downstream hydrograph peak may by greatly increased. However, these effects will be greatest immediately downstream of the dam and decrease as distance of the dam increases. The exact increase in peak flow depends on may factors (inflow hydrograph shape, time of failure, discharge rate, etc.) that are beyond the scope of this research.

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APPENDICES

APPENDIX A

Dam Dimensions

Watershed	Pond Number	Length (m)	Average Height (m)	Base width (m)
Kadake	1	28	0.37	2.0
"	2	18	1.02	2.5
"	3	26	0.77	2.0
"	4	35	0.35	2.0
Eagle	5	20	0.59	3.5
"	6	13	0.89	3.0
"	7	26	0.83	2.5
"	8	19	1.32	3.5
"	9	36	0.74	2.5
Rowan	10	48	0.77	2.0
"	11	7	0.75	2.0
Kadake	12	19	1.18	3.0
"	13	56	0.66	2.5
"	14	106	0.57	3.5
"	15	12	0.30	2.0
Dean	16	32	0.94	4.0
"	17	19	1.09	2.0
"	18	111	0.73	2.0
Rowan	19	18	0.37	1.5
"	20	23	0.49	1.5
Kadake	21	12	0.61	2.5
"	22	25	0.83	2.0
"	23	30	0.53	2.5
"	24	33	0.11	2.0
"	25	29	0.53	2.0
"	26	29	0.07	3.5
"	27	37	0.76	3.5
Saginaw	28	15	0.40	2.5
Straight	29	20	0.62	1.5
Surprise	30	16	0.80	4.0
"	31	2	0.99	2.5
Dean	32	67	0.48	2.0
Straight	33	42	1.22	4.0
Kadake	34	10	1.12	4.0
"	35	30	0.70	2.0
"	36	30	0.87	3.0
"	37	10	0.35	2.0
"	38	37	0.60	4.5
"	39	7	0.05	2.0
"	40	30	0.89	2.5
"	41	15	0.01	2.0
"	42	63	0.45	2.0
"	43	6	0.44	1.0
"	44	132	0.94	3.0

APPENDIX B

Pond Dimension
Summer-stage

Pond Num.	Length (m)	Surface Area (m^2)	Volume (m^3)	Ave. Depth (m)	Max. Depth (m)
1	48	712	173	0.24	1.10
2	41	895	544	0.61	1.50
3	44	1257	922	0.73	1.70
4	83	1799	529	0.29	1.00
5	140	694	452	0.65	1.40
6	57	359	131	0.37	1.00
7	58	797	473	0.59	1.45
8	45	892	1240	1.39	1.65
9	121	3858	2185	0.57	1.50
10	126	11898	5671	0.48	1.40
11	16	96	42	0.44	1.00
12	41	659	366	0.56	1.00
13	161	4838	2754	0.57	1.10
14	53	2992	886	0.30	1.30
15	42	1926	364	0.19	1.05
16	142	2795	2093	0.75	1.90
17	43	343	142	0.41	0.80
18	195	12976	11398	0.88	1.60
19	11	312	132	0.42	1.20
20	102	2168	1063	0.49	1.20
21	35	331	78	0.23	0.65
22	22	281	190	0.68	1.55
23	18	390	226	0.58	1.80
24	10	300	211	0.70	1.45
25	53	649	261	0.40	1.10
26	56	1353	455	0.34	1.20
27	65	1960	1123	0.57	1.55
28	47	461	195	0.42	1.20
29	33	1380	430	0.31	0.80
30	30	327	199	0.61	1.50
31	18	40	10	0.25	0.60
32	87	1867	547	0.29	0.90
33	49	1060	616	0.58	1.30
34	31	208	142	0.68	1.35
35	39	450	174	0.39	0.70
36	80	1048	442	0.42	1.20
37	75	300	111	0.37	0.95
38	20	729	84	0.12	1.10
39	19	190	35	0.19	0.95
40	61	1352	922	0.68	1.50
41	23	155	89	0.58	1.30
42	67	739	272	0.37	1.10
43	7	35	15	0.43	0.75
44	155	7412	6340	0.86	2.10

Pond Dimension
Winter-stage

Pond Num.	Length (m)	Surface Area (m^2)	Volume (m^3)	Ave. Depth (m)	Max. Depth (m)
1	48	712	193	0.27	1.13
2	41	895	544	0.61	1.50
3	44	1264	1013	0.80	1.79
4	83	1897	817	0.43	1.16
5	140	694	452	0.65	1.40
6	57	834	328	0.39	1.445
7	58	849	474	0.56	1.465
8	45	892	1240	1.39	1.95
9	121	6002	4907	0.82	2.05
10	126	11898	5671	0.48	1.40
11	16	96	42	0.44	1.00
12	41	923	586	0.63	1.245
13	161	5668	3840	0.68	1.325
14	53	2992	886	0.30	1.30
15	42	1926	364	0.19	1.05
16	142	9940	6080	0.61	2.50
17	43	911	363	0.40	1.15
18	195	13968	13294	0.95	1.76
19	11	326	142	0.44	1.24
20	102	5077	1545	0.30	1.405
21	35	591	265	0.45	1.115
22	22	281	190	0.68	1.55
23	18	390	226	0.58	1.80
24	10	301	211	0.70	1.455
25	53	1444	605	0.42	1.435
26	56	1353	597	0.44	1.315
27	65	2037	1235	0.61	1.615
28	47	505	200	0.40	1.22
29	33	1380	430	0.31	0.80
30	30	345	282	0.82	1.525
31	18	46	15	0.33	0.73
32	87	2164	776	0.36	0.912
33	49	1094	692	0.63	1.38
34	31	443	250	0.56	1.745
35	39	544	287	0.53	0.935
36	80	1687	1012	0.60	1.615
37	75	330	121	0.37	0.975
38	20	729	84	0.12	1.10
39	19	190	35	0.19	0.95
40	61	1522	963	0.63	1.54
41	23	155	89	0.57	1.30
42	67	793	272	0.34	1.10
43	7	35	15	0.43	0.753
44	155	7866	6953	0.88	2.19

APPENDIX C

Sample Pond Routing
Large-sized pond and a 10-year return interval (50X)

Time	Inflow	Sum Inflow	(2S/dt)-O	(2S/dt)+O	Outflow	Storage	(2S/dt)-O Curve	Storage Curve
(m)	(m³/sec)		(m³/sec)	(m³/sec)	(m³/sec)	(m³)	(m³/sec)	(m³)
0	0		27.26		0	4907		4907
6	.005	.005	27.26	27.27	.001	4907.82	.001	4907.82
12	.010	.015	27.27	27.28	.003	4909.95	.003	4909.95
18	.153	.026	27.29	27.30	.006	4913.00	.006	4913.00
24	.020	.036	27.31	27.32	.010	4916.69	.010	4916.69
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
324	.276	.547	28.47	29.00	.262	5172.27	.262	5172.27
330	.281	.557	28.50	29.03	.267	5177.45	.267	5177.45
336	.286	.568	28.52	29.06	.272	5182.63	.272	5182.63
342	.294	.580	28.55	29.10	.277	5188.20	.277	5188.20
348	.289	.583	28.57	29.13	.282	5192.48	.282	5192.48
354	.284	.573	28.57	29.14	.283	5193.90	.283	5193.90
360	.279	.562	28.57	29.13	.283	5193.34	.283	5193.34
366	.274	.552	28.56	29.12	.281	5191.38	.281	5191.38
372	.268	.542	28.55	29.10	.278	5188.45	.278	5188.45
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
696	.000	.000	27.30	27.32	.009	4915.76	.009	4915.76
702	.000	.000	27.29	27.30	.006	4913.15	.006	4913.15
708	.000	.000	27.28	27.29	.004	4911.33	.004	4911.33
714	.000	.000	27.28	27.28	.003	4910.06	.003	4910.06
720	.000	.000	27.27	27.28	.002	4909.17	.002	4909.17
TOTAL=16.761					TOTAL=16.766			

PERCENTAGE REDUCTION = 3.70