Dams in Minnesota

A Report to the Minnesota House and Senate Environment Committees (as required by Laws of 1994, Chapter 632, Section 5, Subdivision 2)

February 1995

Minnesota Department of Natural Resources
Division of Waters

Pursuant to 1994 Minn. Laws Chap. 632
Sec. 5 Subd. 2

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<u>Estimated Cost of this Report:</u> $11,000.

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A Report to the Minnesota House and Senate Environment Committees
by the Minnesota Department of Natural Resources, Division of Waters

I. INTRODUCTION

• Legislative Directive

Laws of 1994, chapter 632, section 5, subdivision 2 directed the Department of Natural Resources (DNR) to examine dam management issues and make a report:

> *"The commissioner of natural resources shall conduct a study of dams on waters of the state. The study must investigate the type and number of impoundments that exist, their condition, and their probable future life span. The study also must examine dam issues and make recommendations for policies regarding Minnesota dams, including renovation versus removal, the impact on the ecology of the waterway, any need for additional construction, and the potential for hydropower or drinking water supplies. The commissioner must report back to the house and senate environment committees by February 15, 1995."*

• Scope of this Report

There are on the order of 2,000 structures on Minnesota waters that impound water and could be defined as dams. About two-thirds of them are owned by governmental entities, and one-third by the private sector. Most dams in Minnesota are less than 30 feet high. The tallest concrete dams, such as at Byllesby Lake, Zumbro Lake, and Rapidan, are 60 feet to 70 feet high. Some tailings dams on the Iron Range are over 100 feet high and several miles long.

Roughly 900 of these 2,000 structures are subject to the jurisdiction of state dam safety rules based on their size (see page 12 for details). This report will focus primarily on these dams, even though all dams on protected waters are subject to protected waters permit rules.

Dams owned by federal agencies are exempt from state dam safety rules; however, those meeting the size threshold of state dam safety rules are included in the statistics shown in this report.

Because it is not practical to discuss each of the 900 regulated dams individually, the report presents information by categories of dams. Dams can be categorized by purpose, age, ownership, location, etc. Often dams built for the same purpose will share other characteristics and present similar management issues. It should be understood that there will be exceptions to the generalizations because each dam has unique characteristics.

• Use of this Report

It is hoped that the information and policy recommendations contained in this report will assist in setting future public policy on dam management.

II. TYPES AND NUMBERS OF DAMS IN MINNESOTA

A. Categorizing Dams by Water Body Type

Dams can be categorized by the type of water body they impact or create. These categories are useful in assessing environmental, public safety, and other public impacts.

- **River Dams**

Most dams in this category are mill dams, hydropower dams, and navigation dams. They are especially significant because of their size, locations, ecological impacts, and functions.

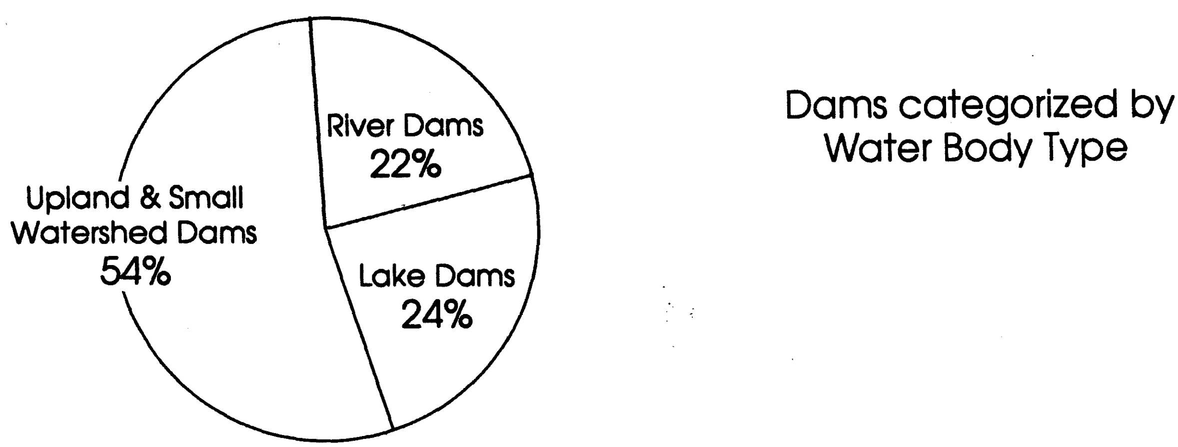
- **Lake Dams**

The majority of dams in this category are the Works Progress Administration lake outlet dams built in the 1930's. The purpose for most of these dams was to help maintain desirable water levels during dry periods. Many lake outlet dams are not subject to state dam safety rules because they are less than six feet high.

- **Upland and Small Watershed Dams**

Dams in this category are typically located on wetlands, intermittent streams or in coulees, where they capture runoff from rainstorms or snowmelt. Most of the dams in this category were built for the purpose of erosion control, flood control, or enhancing waterfowl habitat. Some of these dams are small, agricultural flood control dams built on private farms with technical assistance provided by the federal Natural Resources Conservation Service (formerly the Soil Conservation Service). Figure 1 shows a breakdown of the 900 regulated dams by water body type.

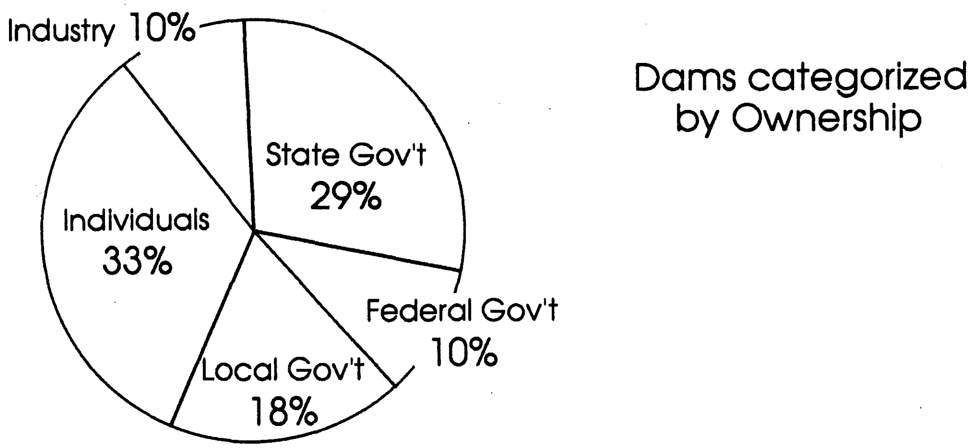
Figure 1



B. Categorizing Dams by Ownership

Of the 900 regulated dams in Minnesota roughly 57% are publicly owned and 43% privately owned. About one-half of the public dams are owned by the DNR, and about three-quarters of the private dams are owned by individuals. Figure 2 shows a breakdown of regulated dams by ownership.

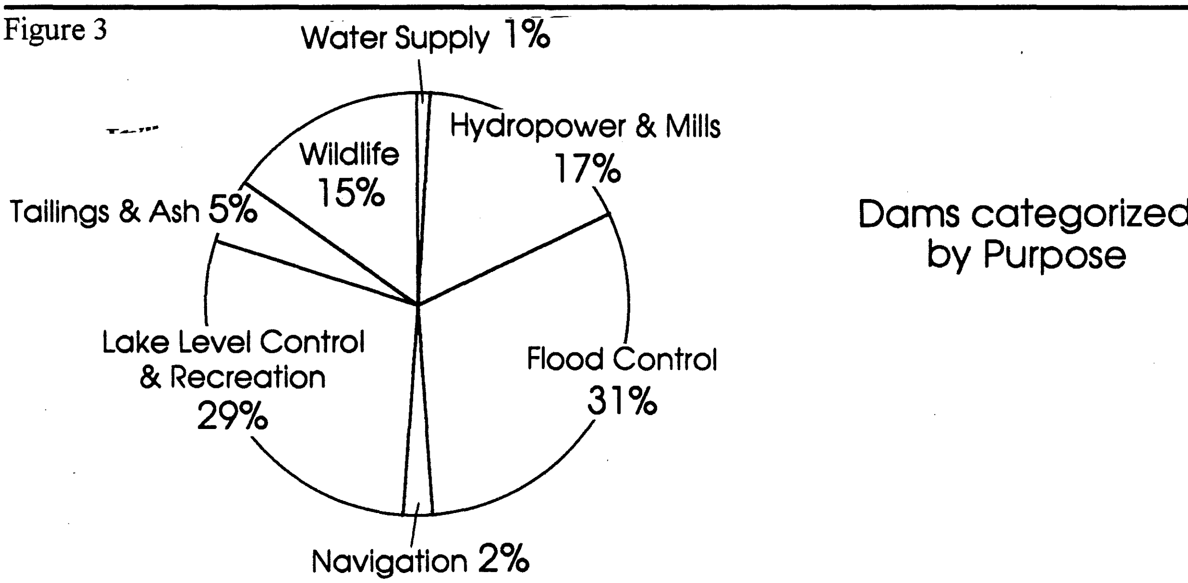
Figure 2



C. Categorizing Dams by Purpose

The most common way to categorize dams is by their purpose. Sometimes the primary purpose of a dam will change over its life span, and some dams are planned and designed to serve multiple purposes. Figure 3 shows a breakdown of dams by primary purpose.

Figure 3



• Hydropower

Hydropower dams impound water to be used to operate turbines, which turn generators to produce electrical power. The 32 active hydropower dams in Minnesota currently have a combined total electrical capacity of about 215 megawatts. Over one-third of this electricity is generated by a single facility--the Thomson Plant on the St. Louis River owned by Minnesota Power Company.

Seventeen of these dams are owned by three utility companies--Minnesota Power, Otter Tail Power Company, and Northern States Power. Nine are owned by local governmental units that also produce power for profit. Six are owned by manufacturing companies, such as Potlatch Corporation, which use the power directly in their manufacturing plants. Hydropower dams are generally located on medium or large rivers and are typically over fifteen feet high. They are regulated by the Federal Energy Regulatory Commission (FERC) and the state. Figure 4 shows the location, ownership, and regulatory status of hydropower dams currently operating in Minnesota.

• Flood Control

Flood control dams are designed to store large volumes of runoff from rainstorms or snowmelt and release it slowly in order to reduce downstream peak flood levels, flood damages, and erosion.

The federal Natural Resources Conservation Service (NRCS) has been the largest builder of flood control dams in Minnesota. The peak period of their dam construction was between 1960 and 1985. NRCS flood control dams number about 300. Most are located in rural areas and were built for the primary purpose of protecting agricultural land. A complex of seven NRCS flood control dams are currently being built around Rochester. They are fairly large, high hazard dams, built to provide urban flood control. The NRCS dams were built under cooperative agreements with private landowners or local governmental sponsors who take ownership of the dams. Because they are not federally owned, these dams are subject to state dam safety rules.

Although the Army Corps of Engineers is generally considered a major federal dam builder, it has built only three dams in Minnesota for the primary purpose of flood control. They are the Orwell Dam on the Otter Tail River near Fergus Falls, the Lower Red Lake Dam on the Red Lake River in Clearwater County, and the White Rock Dam on the Bois de Sioux River in Traverse County. These three dams are federally owned and not subject to state dam safety rules.

Local watershed districts have built many flood control dams without federal assistance from either the NRCS or the Corps of Engineers.

Figure 4

MINNESOTA HYDROPOWER SITES (BY OWNER)

#	OWNER	DAM NAME	COUNTY	RIVER	CAPACITY (MW)	FERC REGULATED
UTILITIES:						
1	MP (Minnesota Power)	Blanchard	Morrison	Mississippi	18.0	Yes
2	MP	Fond Du Lac	Carlton	St. Louis	12.0	Yes
3	MP	Knife Falls	Carlton	St. Louis	2.4	Yes
4	MP	Little Falls	Morrison	Mississippi	4.7	Yes
5	MP	Pillager	Morrison	Crow Wing	1.5	Yes
6	MP	Prairie River	Itasca	Prairie River	1.1	Yes
7	MP	Scanlon	Carlton	St. Louis	1.6	Yes
8	MP	Sylvan	Cass	Crow Wing	1.8	Yes
9	MP	Thomson	Carlton	St. Louis	72.6	Yes
10	MP	Winton	Lake	Kawishiwi	4.0	Yes
11	NSP	St. Anthony (Upper)	Hennepin	Mississippi	12.4	Yes
12	OTPC (Otter Tail Power)	Bemidji	Beltrami	Mississippi	0.7	No
13	OTPC	Central	Otter Tail	Otter Tail	0.4	Yes
14	OTPC	Dayton Hollow	Otter Tail	Otter Tail	1.0	Yes
15	OTPC	Friberg	Otter Tail	Otter Tail	0.6	Yes
16	OTPC	Hoot Lake	Otter Tail	Otter Tail	1.0	Yes
17	OTPC	Pisgah	Otter Tail	Otter Tail	0.5	Yes
PAPER COMPANIES:						
18	Blandin	Blandin	Itasca	Mississippi	2.1	Yes
19	Boise Cascade	International Falls	Koochiching	Rainy	14.5	Yes
20	Champion	Sartell	Stearns	Mississippi	9.5	Yes
21	Potlatch	Brainerd	Crow Wing	Mississippi	3.3	Yes
22	Potlatch	Cloquet	Carlton	St. Louis	6.5	Yes
OTHER:						
23	Ford Motor Co.	Lock & Dam No. 1	Hennepin	Mississippi	17.9	Yes
CITY:						
24	Granite Falls	Granite Falls	Yellow Medicine	Minnesota	1.2	Yes
25	Hastings	Lock & Dam No. 2	Dakota	Mississippi	4.0	Yes
26	Lanesboro	Lanesboro	Fillmore	Root	0.1	No
27	Redwood Falls	Redwood Falls	Redwood	Redwood	0.6	No
28	Rochester	Zumbro	Wabasha	Zumbro	2.3	No
29	St. Cloud	St. Cloud	Stearns	Mississippi	8.9	Yes
30	Thief River Falls	Thief River Falls	Pennington	Red Lake	0.6	Yes
COUNTY:						
31	Blue Earth	Rapidan	Blue Earth	Blue Earth	4.9	Yes
32	Dakota and Goodhue	Byllesby	Dakota/Goodhue	Cannon	1.8	Yes
TOTAL:					214.5	

• Lake Level Control/Recreation

Lake level control/recreation dams were built to raise natural water levels in rivers or lakes to improve recreational oppurtunities, or to protect against extreme low water conditions in the event of drought.

The majority of these types of dams are lake outlet dams built by the federal Works Progress Administration in the late 1930's. They primarily benefit riparian landowners and recreational users. The State of Minnesota became owner and caretaker of most of these dams. Primary examples include dams at the outlets of Mille Lacs Lake and Otter Tail Lake. Some important lake outlet dams are owned by local governmental units. A primary example is Gray's Bay Dam on Lake Minnetonka, which is owned by the Minnehaha Creek Watershed District.

• Water Supply

Water supply dams are built to store water for some particular use, such as domestic water supply, manufacturing process water, or cooling water. Many water supply dams were built by railroad companies in the Red River Valley to provide a reliable source of water for steam locomotives. As potable ground water was not available to settlers, they utilized the railroad dams for drinking water and also built their own dams. Most of these dams are no longer needed because many cities have switched to wells or are now connected to rural water supply systems.

The dam on the Red Lake River at East Grand Forks is an example of a dam built for the primary purpose of water supply for domestic consumption. There is a single purpose industrial water supply dam near Forbes, Minnesota that provides make-up water for Eveleth Taconite. Of the other cities that use surface waters from dams for domestic consumption, all are multipurpose dams.

Water in Minnesota is in short supply in the western regions where there is less precipitation and the geology is less conducive to productive wells. Occasionally there is interest from this area for new sources of water, either by building new dams or changing the operation of existing dams.

• Mill Dams

Mill dams were built on rivers and incorporated waterwheels or turbines to produce mechanical power to grind grains into flour, saw logs, or cut quarry stone.

More than 1,000 mill dams were known to have been built between 1850 and 1900. The majority of mill dams were built in rural locations that provided relatively stable supplies of stream flow. They were usually built to impound between six and twelve feet of water. Towns often developed around mill dams, especially in southern Minnesota. Most of these dams no longer exist, and only Schechs Mill (in southeast Minnesota near Caledonia) is still used to grind corn. Only about 120 mill dams remain that are regulated, and most of these have been reconstructed one or more times. Most of the remaining mill dams are owned by cities, and many are in poor condition. The rotating currents produced below these "low head" dams are often much stronger than they appear, and mill dams account for a disproportionate share of drownings.

• Navigation

The earliest navigation dams in Minnesota were built by logging companies to capture water for sluicing logs downstream. Most of these dams have vanished.

The primary navigational dams remaining in Minnesota are the federal dams built on the Mississippi River system to assist commercial barge traffic. The federal government began construction of the six Mississippi River headwaters reservoirs in the 1880's. The headwaters reservoirs were justified to Congress on the basis of benefiting river navigation, but the primary benefits went to downstream waterpower interests and upstream recreational interests. The locks and dams on the Mississippi River were also an initiative of the federal government, which undertook the construction of a nine-foot river channel from St. Louis to St. Paul for the purpose of improving commercial navigation. Lock and Dam 1 (Ford Dam) was completed in 1917, and Lock and Dam 2 (Hastings Dam) in 1930. Seven additional locks and dams below Hastings on the Minnesota-Wisconsin boundary were built in the 1930's and 1940's. The upper and lower locks and dams at St. Anthony Falls were built in the late 1950's and early 1960's, bringing the total number of locks and dams on Minnesota's portion of the Mississippi River to eleven. The federal Army Corps of Engineers is responsible for maintenance and operation of both the headwaters reservoirs and the locks and dams.

Figure 5 lists the six Mississippi River headwaters reservoirs and the navigational locks and dams.

Figure 5

Dam	Nearest City
Leech Lake	Federal Dam
Winnibigoshish Lake	Deer River
Pokegama Lake	Grand Rapids
Big Sandy Lake	McGregor
Cross Lake	Cross Lake
Gull Lake	Brainerd
Upper St. Anthony Lock & Dam	Minneapolis
Lower St. Anthony Lock & Dam	Minneapolis
Ford Dam (Lock & Dam #1)	Minneapolis
Lock & Dam #2	Hastings
Lock & Dam #3	Red Wing
Lock & Dam #4	Kellogg
Lock & Dam #5	Winona
Lock & Dam #5A	Winona
Lock & Dam #6	Winona
Lock & Dam #7	Dresbach
Lock & Dam #8	Brownsville

• Wildlife Impoundments

Wildlife impoundments are built to create or enhance shallow water bodies to provide habitat for wildlife, particularly waterfowl. Several hundred dams have been built for the purpose of creating or enhancing waterfowl habitat, primarily by state and federal agencies. Most wildlife impoundments are installed in the headwaters of watersheds. Most of the dams associated with these impoundments are exempt from state dam safety rules either because they are less than six feet in height or are owned by federal agencies like the U.S. Fish and Wildlife Service.

The DNR Section of Wildlife has developed and maintains approximately 300 impoundments over 10 acres in size totalling approximately 115,000 acres. About 70 are subject to state dam safety rules. The largest is Swan Lake in Nicollet County, which includes 10,000 acres. Projects are generally carried out either within state owned Wildlife Management Areas or on designated wildlife lakes. Operable low head dams have been installed at the outlets of many natural wetlands to allow management of water levels for the purpose of managing aquatic plants to improve habitat. Without water level management, much of the aquatic vegetation in many of these wetlands would be lost along with wildlife values.

• Tailings and other Waste Containment Dams

Tailings and waste containment dams are built for the purpose of reducing pollution by preventing polluting materials from reaching rivers and lakes and for recycling of industrial process water.

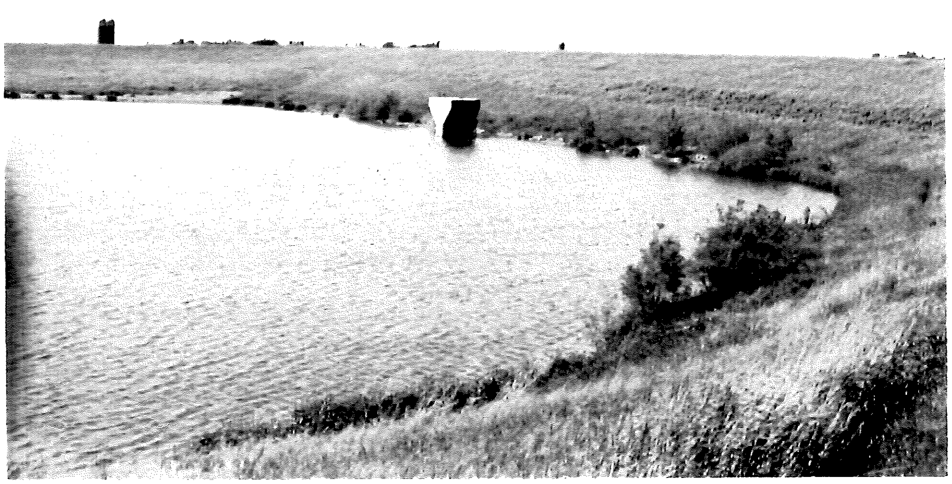
Minnesota's Iron Range contains about 50 dams built primarily to contain tailings resulting from taconite mining. A few of these dams exceed 125 feet in height and 4 miles in length. They are the largest dams in Minnesota, and they are subject to state dam safety rules. Other waste containment dams regulated by the DNR include coal ash containment dams at coal-burning power plants.

Waste containment dams that fall outside the jurisdictional threshold of state dam safety rules may still be regulated by the Minnesota Pollution Control Agency because of their potential to cause pollution.

D. Photos of Common Dam Types

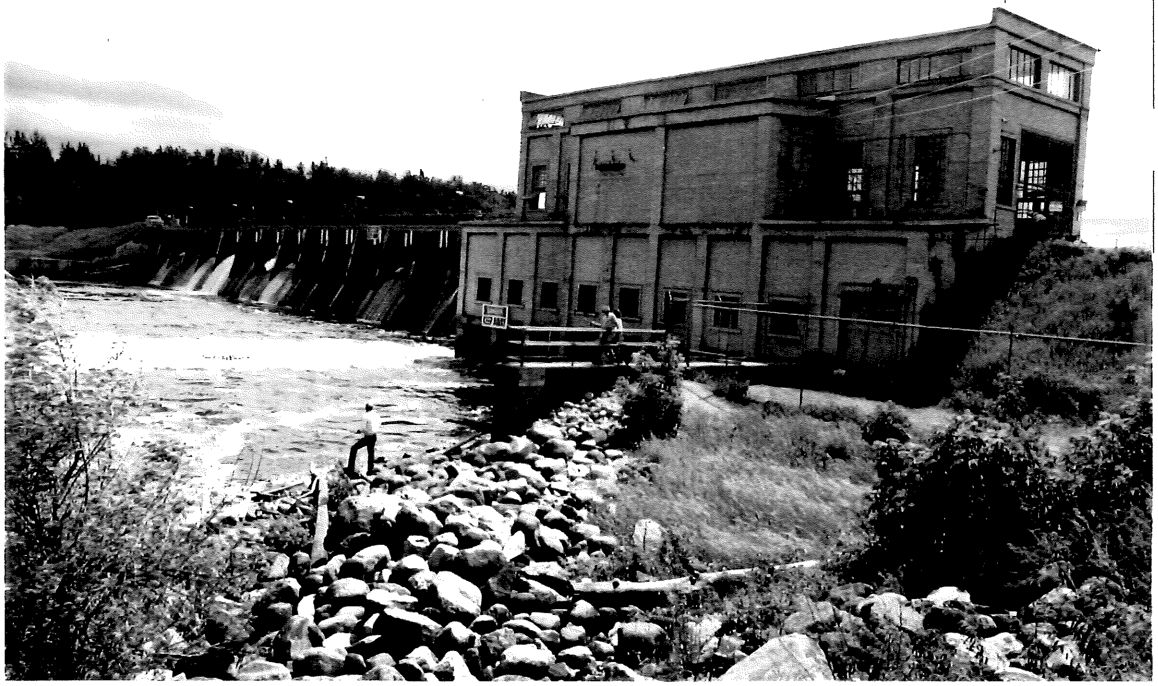
Wildlife Dam
near Fosston,
Polk County

Mill Dam
on Cannon River
in Northfield,
Rice County

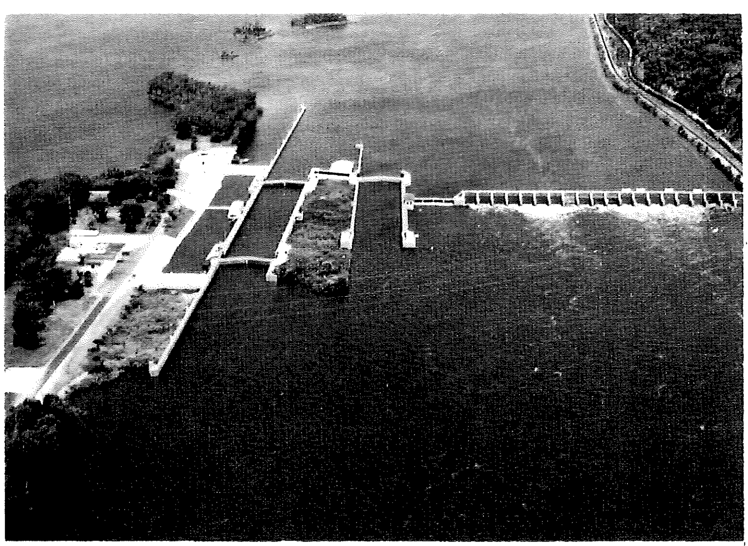


Flood Control Dam
Schoper - Bush Reservoir
near Springfield,
Cottonwood County

Lake Level Control Dam
at Onamia Lake,
Mille Lacs County



Hydropower Dam
on Crow Wing River,
in Pillager,
Cass County



Navigation Dam
Lock & Dam #2
in Hastings,
Dakota County

III. CONDITION AND LIFE SPAN OF DAMS IN MINNESOTA

The average life expectancy of a dam is roughly 75 years, but it varies considerably depending on design, the quality of the construction work, and location. Good maintenance can extend the life span, and lack of maintenance can shorten it. Many of the dams controlling water levels on our recreational lakes are deteriorating and need repairs to extend their useful lives.

Many early dams failed prematurely due to overtopping by flood waters because they were built with inadequate hydraulic capacity. Modern engineering standards require an analysis of the contributing watershed behind a dam and dams are designed to safely pass a predetermined design flood.

Since dams built for similar purposes generally share similar conditions and life spans, purpose categories will be used to discuss the condition and life span of dams.

A. Condition and Life Span of Dams By Dam Purpose

• Hydropower Dams

One of the earliest hydropower facility in Minnesota was built at St. Anthony Falls in Minneapolis in the 1880's. The majority of hydropower dams were constructed between 1900 and 1920. They were designed by engineers and built out of concrete and/or stone. Only 32 are still operated. Those no longer producing power and not regulated by the Federal Energy Regulatory Commission are in fair to poor condition, as is the case with the Coon Rapids Dam. Many have deteriorated and will eventually require renovation or removal. Those hydropower dams still in operation that are regulated by the Federal Energy Regulatory Commission tend to be in fair to good condition because they generate revenue for maintenance.

• Flood Control Dams

NRCS designed flood control dams built with earthen embankments and concrete spillway conduits are generally in good condition. Many of these are owned by watershed districts. Those built with steel conduits vary in condition from good to poor. Most of these are owned by private individuals and need maintenance. Burrowing animals are attracted to these poorly maintained dams and can destroy the integrity of the earthen embankments. These dams are also prone to failure due to corrosion of the steel conduit. This type of dam is a growing maintenance problem.

• Lake Level Control/Recreation Dams

Most of Minnesota's lake level control/recreation dams are over 50 years old. Standard designs using formed concrete were common in these dams. Although the quality of the concrete varied considerably, most of these dams are in fair condition. The DNR owns most of these dams and provides for periodic inspection, maintenance, and repairs. The DNR Division of Waters allocates one full-time equivalent position to conduct routine maintenance and has expended roughly $300,000 of bonding funds annually to contract for major repairs on state owned dams.

- **Water Supply Dams**

The condition of water supply dams in Minnesota varies widely, but are generally better than average owing to their continuing usefulness and the need to maintain them.

- **Mill Dams**

Some mill dams were built by early settlers before Minnesota entered statehood in 1858, but the peak building period was between 1860 and 1900. Many mill dams failed within 30 years of original construction and were never rebuilt. Most of those that remain have been reconstructed at least one and often twice. Most of the remaining mill dams were last reconstructed over 50 years ago and are in fair to poor structural condition.

- **Navigation Dams**

The federal navigation dams on the Mississippi River are probably the best maintained dams in Minnesota. The Corps of Engineers performs regular maintenance and updates electrical and mechanical controls. The Corps of Engineers considers 50 years to be a reasonable time period between major rehabilitation projects.

- **Wildlife Impoundment Dams**

Embankment structures built with steel culvert spillways are expected to last 20-25 years between major repairs depending upon the acidity of the water, and those built with concrete culverts about 50-75 years. Steel sheet piling structures generally last 25-50 years. Annually about $75,000 in DNR Section of Wildlife funds, including personnel time, is spent to maintain wildlife impoundments structures.

- **Tailings and Other Waste Containment Dams**

The first tailings dams were built over 100 years ago. Tailings dams are currently serving seven active mining operations, and are in generally good condition. Many of the older tailings dams are in poor or unknown condition. Long-term management of active tailings dams must now be addressed in mine reclamation plans.

Power plant ash containment dams are generally well maintained by power companies.

B. Recent Dam Failures

There have been several dam failures in Minnesota in recent years. The main consequence of the failures has been the cost to repair or remove the dams. Damages from released waters have not been significant, and there have been no lives lost due to these dam failures. Since 1980, dam failures have occurred at Stewartville in Olmsted County, Split Rock Creek State Park in Pipestone County, Locke Lake in Anoka County, Roseau Water Management Area in Roseau County, Lower St. Anthony Falls in Hennepin County, Bernings Mill and Hanover in Wright County, and Windom in Cottonwood County. These failures demonstrate the need to perform continuing inspection and maintenance of dams. The failure of the DNR dam at Split Rock Creek State Park resulted in three South Dakota property owners alleging damages totalling $813,000.

A large number of high hazard dams are owned or regulated by the federal government and are in good condition. Other high hazard dams are inspected annually by the DNR. As these dams age the need for repair will increase.

C. Future Needs for Repair, Reconstruction, or Removal

The DNR estimates that approximately $1,000,000 per year in bonding appropriations over the next 50 years will be needed to address the maintenance needs of Minnesota's aging infrastructure of publicly owned dams. All dams are in need of periodic maintenance. Priority for dam repair funds will be given to projects that have the greatest impact on public safety, the environment, recreation, maintaining fish and wildlife habitat, and hydropower. Emergency situations and partial failures also occur periodically, which require immediate repair or removal.

IV. STATE DAM SAFETY PROGRAM

Minnesota's dam safety program was created in 1978 in response to the federal Dam Safety Act. A series of major dam failures that killed scores of people in the 1970's prompted Congress to pass the Act to improve dam safety nationally. Minnesota's program is now staffed by two engineers and one state dam maintenance worker.

Minnesota's program includes: enabling legislation, agency rules, dam database, permits, inspections, and cost share grants for dam repairs.

- **Enabling Legislation**

Minnesota Statutes, section 103G.515 authorizes the DNR commissioner to inspect dams and issue orders directing dam owners to make necessary repairs. The same section directs the commissioner to adopt rules governing dam safety.

- **Agency Rules**

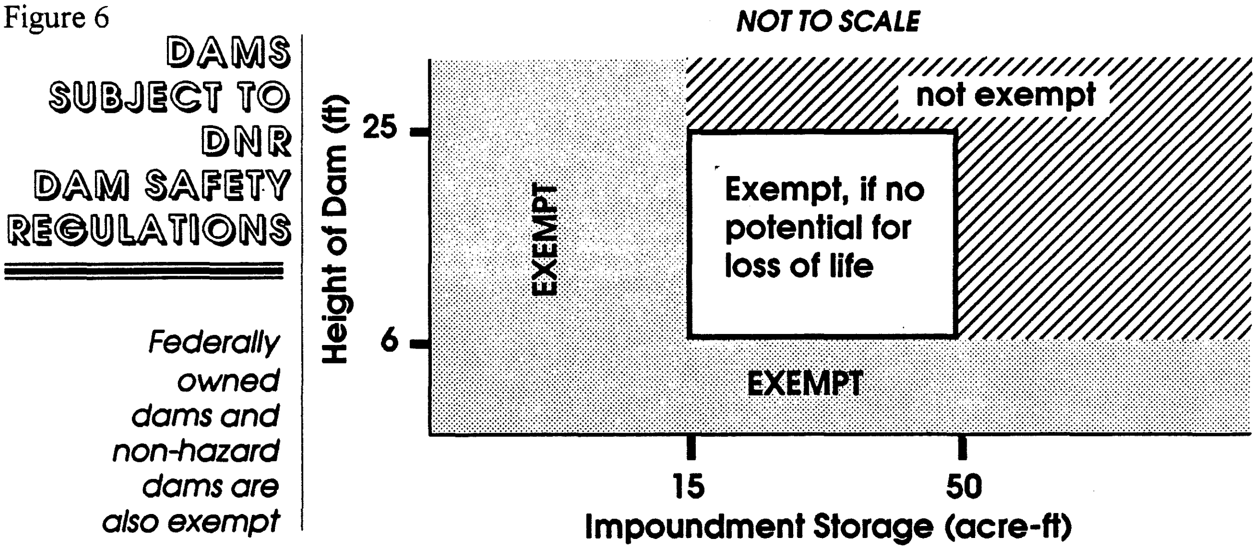
Minnesota Rules, parts 6115.0300 through 6115.0520 govern the state dam safety program. Among other things, the rules define which dams are subject to state jurisdiction, and establish dam hazard classes.

<u>State Jurisdiction Over Dams</u>

State dam safety regulations apply only to structures that pose a potential threat to public safety or property. State dam safety rules do not apply to dams that are so low or retain so little water as to not pose a threat to public safety or property. The energy that can cause damage if a dam failure occurs is a product of the height of the dam and the amount of water impounded.

Dams 6 feet high or less, regardless of the quantity of water they impound, and dams that impound 15 acre-feet of water or less, regardless of their height, are exempt from state dam safety rules. Dams that are less than 25 feet high and that impound less than 50 acre-feet are also exempt from state dam safety rules unless there is a potential for loss of life due to failure or misoperation. Figure 6 shows these criteria in a graphical form.

Figure 6



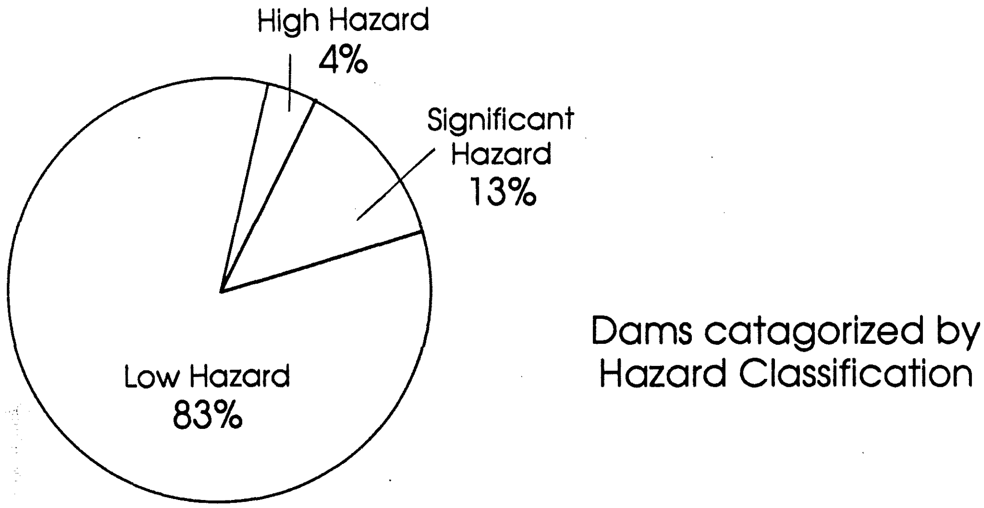
Hazard Classification of Dams

The rules classify dams according to the property damages and human costs that could accrue in the event of failure or misoperation. Consequences of potential dam failures are examined assuming worst case scenarios, discounting the condition of the dam. Minnesota has about 40 dams where failure could potentially cause loss of life. The cities of Cannon Falls, Rochester, and Faribault have the most potential for damages due to a dam failure. Each dam is assigned to one of the following hazard classes:

> Class I (High Hazard) - Probability of loss of life or serious hazard, or damage to health, main highways, high-value industrial or commercial properties, major public utilities, or serious economic loss to the pulic.
>
> Class II (Significant Hazard) - Possible health hazard or probable loss of high-value property, damage to secondary highways, railroads or other public utilities, or limited economic loss to the public.
>
> Class III (Low Hazard) - Property losses restricted mainly to rural buildings and local county and township roads.

Figure 7 shows a breakdown of regulated dams by their hazard classification.

Figure 7



• Dam Database

In cooperation with the Federal Emergency Management Agency and the Association of State Dam Safety Officials the DNR Division of Waters maintains Minnesota's component of the National Dam Inventory (NATDAM). NATDAM presently includes information only on those dams meeting the threshold of state dam safety rules. About 900 dams are currently listed in the system. NATDAM can store information on dam name, location, purpose, hazard classification, structural condition, date of last inspection, and about 30 other data elements.

• Permits

The DNR Division of Waters processes on average 20 permit applications per year. Permits are required to perform major maintenance, modify dam operation, reconstruct a dam, remove a dam, transfer dam ownership, or build a new dam.

• Inspections

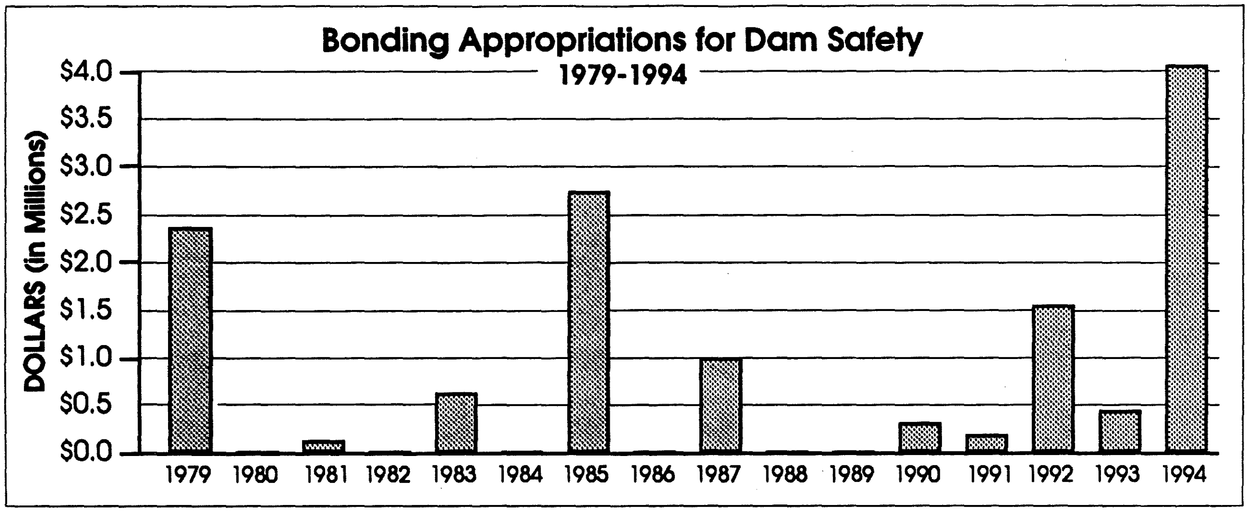
High hazard dams are inspected annually and lower hazard dams are inspected less frequently by DNR dam safety engineers.

Inspections performed by professional engineers working for the Corps of Engineers, the Natural Resources Conservation Service, the Federal Energy Regulatory Commission, or private dam owners are not duplicated by the DNR. Dams being built or having major repair also require state inspection. High hazard dams have emergency action plans, which need to be monitored and revised as necessary on a periodic basis. Some dams have instrumentation to warn of internal changes that may indicate a deterioration of their structural integrity, and these need to be checked on a regular basis.

• **Repairs and Removals**

Minnesota Statutes, section 103G.511 authorizes a state dam safety cost share program. The DNR commissioner may make grants to local units of government for dam repair, reconstruction, or removal. The statute directs the commissioner to annually prepare and submit to the legislature a prioritized list of needed dam safety projects, including both local and state owned dams. To date, appropriations to fund dam safety projects have come almost entirely from capital bonding. Figure 8 shows the history of dam safety project funding from 1979 through 1994.

Figure 8



V. DAM RENOVATION VERSUS REMOVAL

Most dams serve important purposes and need to be maintained, but some dams no longer provide public benefits and their continued repair and maintenance is not in the public interest. There are three main reasons why removal is becoming a practical alternative to repair for some dams:

1) cost--many dams in Minnesota are very old and in poor structural condition, and their reconstruction can be expensive;

2) emphasis on public safety--some dams act as "drowning machines" (responsible for over 30 deaths in the last twenty years); and

3) heightened environmental concern--dam removal can provide an opportunity to restore a river to a free flowing condition to benefit recreation, movement of fish, and restoration of the entire riverine ecosystem.

Before supporting any request for state cost share funds for dam reconstruction, the DNR Division of Waters asks the question: "Has the option of dam removal been considered?" A dam owner needs to consider the removal option when the dam has reached the end of its effective life span. The decision criteria to evaluate in making this decision are the same criteria the DNR considers in determining the priorities of dam safety project needs.

A. Decision Criteria

The criteria or factors to be considered in determining whether to reconstruct or remove an aging dam include: public safety, economic impacts, ecological impacts, recreational impacts, cost, historical significance, and public support.

• Public Safety

Dams threaten public safety by virtue of the threat from sudden failure and the potential for drownings. Low head mill dams with deep tailwater areas are often referred to as "drowning machines." At the Welch Mill Dam on the Cannon River, which was removed in 1994, there were six documented fatalities just within the last 20 years. One dam on the Red River is known to have caused the death of more than 15 people. One person drowned at the Flandrau Dam in New Ulm in 1994. The Flandrau Dam will be removed prior to the 1995 open water season.

• Economic Issues

The removal of a dam can have both positive and negative economic impacts. Positive impacts can be restoration of scenic rapids, whitewater for kayaking enthusiasts, and improved river fisheries. Dam removals can adversely impact public utilities, navigation, highways, and property values and businesses dependent on the impoundment. Other properties in the vicinity may be benefitted by the tourism generated by a reservoir. On some dams, very large numbers of seasonal homes may be affected. Minnesota law is not clear as to the responsibility of a dam owner to pay for and maintain a dam for the convenience of others that benefit, such as shoreline owners.

• Ecological Impacts

Dams on rivers have impacts on the physical and chemical nature of the river as well as the plants and animals inhabiting its waters. Impacts occur above and below a dam. The effects of building a dam on the ecology of a river may be noticed immediately or may occur over many years. The magnitude of these effects varies tremendously and is dependent on factors such as the size and gradient of the river, dimensions of the dam, dam operation, watershed characteristics, and the living requirements of fish and other life found in the river.

The ecological impacts of river dams can be generally grouped into changes in water quality, alterations to sediment transport, restrictions to fish movement and access to important habitats, and effects of changed flow characteristics (frequency, magnitude, and duration of flood events).

Water quality changes occur in the reservoir because of nutrient and sediment accumulation. Reservoirs increase water temperatures and this may result in periods of oxygen depletion. Fish and other life that thrive in a reservoir are lake-adapted organisms that differ from the original river life.

River dams impose barriers to fish movement thus fragmenting habitat. Many fish move upstream in the spring to spawning habitat. After hatching, fish move downstream to suitable juvenile and adult habitats. Some species move downstream in the fall to suitable overwintering sites.

Changes to flow characteristics can result in limited nutrient (food) inputs from riparian areas due to reductions in the frequency and magnitude of overbank flood events. Hydropower dams that are operated in a peaking mode (where water is stored in the reservoir during off-peak hours to increase generating capacity during peak hours of power demand) may increase sediment loads by causing excessive scouring of banks, and may actually strand fish on gravel bars, if downstream discharge fluctuations are severe.

A more detailed and technical discussion of the ecological impacts of river dams is included as Appendix A.

- **Recreational Impacts**

Reservoirs impounded by river dams often provide significant local recreational resources. They provide opportunities for boating, lake fishing, and other recreational activities that would not otherwise be available in communities lacking natural lakes. A few large reservoirs provide regionally-significant recreational resources. In water-rich Minnesota, however, with approximately 12,000 natural lakes, reservoirs are not as significant in the overall recreation picture as they are in states having few lakes.

Free-flowing rivers provide an entirely different type of recreational resource than reservoirs. Rivers provide unique experiences for canoeing, kayaking, and bank fishing, while reservoirs provide opportunities similar to lakes for power boating, sailing, and boat fishing. More importantly, the aquatic ecosystem, including the fishery, of free-flowing riverine systems is very different from that of reservoirs, often supporting different types of fish populations.

When rivers are dammed, the reach upstream of the dam is radically changed from a riverine ecosystem to what is essentially a lake ecosystem, thus changing the recreational fishing experience. Streamflow and water level manipulation at hydropower dams can have a negative impact on recreational use of a river. Recreation opportunities are also changed by the creation of barriers to navigation for canoeists and boaters, by elimination of current which is essential to river-type recreational experiences, and by significant impacts to aesthetics and the physical environment. Dams also present a safety hazard to recreational river users, requiring barriers, signing, and other safety measures on the part of dam owners.

Given the abundance of natural lakes in Minnesota that are available for recreation, new reservoirs generally are not justified from a recreational standpoint, when consideration is given to the significant changes that their creation makes to natural conditions. If anything, we have greater need for free-flowing streams for recreation than we do for more lake-type experiences.

• Cost

Cost is always a major factor in deciding whether a dam should be renovated or removed. Generally, renovating or rebuilding a dam is two to five times the cost of removing the dam.

• Historical Significance

There are a number of historic preservation issues related to the renovation or removal of dams. Minnesota's history of dam construction encompasses a variety of significant developments. Some of the earliest impoundment features that still exist are logging and milling related. Other dam types of historical interest are hydropower dams and certain dams built for recreational or conservation purposes, for example, Civilian Conservation Corps dams in state parks.

The State Historic Preservation Office (SHPO) of the Minnesota Historical Society has responsibility under both state and federal law to provide recommendations for agencies considering renovation versus removal of dams that are over 50 years old. The SHPO reviews dam related projects that involve federal funding or require federal permits, and projects requiring state environmental review.

Another historic preservation concern related to dam removals or, in some cases, temporary lowering of reservoirs is that archaeological sites may be exposed to vandalism or other site disturbing activities. Depending on the specific body of water, it may be prudent to have a cultural resource survey completed during initial reservoir drawdown.

Agencies are directed by law to cooperate with the SHPO, and historic preservation could block removal of certain dams. Historic preservation law could also significantly raise the cost of some removal projects where both a historic study and full documentation of all structural features is required. This can cost $10,000 or more.

• Public Support

The removal of a dam can have impacts on the aesthetics and image of a town. Residents may feel the town's identity is tied to the dam or the reservoir created by the dam. Local opposition to the removal of a dam can be strong, especially in cases where the dam has historical significance. Removal of a dam and elimination of the impoundment can result in the real or perceived loss of recreational benefits. People with residences directly on the impoundment may also fear loss of property value.

B. Conclusions

Some general conclusions about renovation versus removal of dams can be drawn by applying the aforementioned decision criteria.

- Before public money is expended on renovations, it needs to be determined that public benefits outweigh the costs; if not, dam removal would be the preferred management option.

- A few dams will be removed as they deteriorate and fail.

- Most dams to be removed will be deteriorating or failed mill sites on rivers.

- Lives will be saved by removing some dams.

- It will be very difficult to convince a local unit of government to remove their dam if the dam still provides benefits such as hydropower, flood control, or recreation.

- Avoidance of potentially high repair costs, liability for dam failure, and public safety are the primary incentives for an owner to remove a dam.

- More dams will be removed if the state provides cost share funding. Removal of publicly owned dams saves the public money both short-term and long-term because it eliminates the need for maintenance and repairs.

- Removing a dam most likely will have positive impacts on both the recreational and ecological value of a river, therefore re-establishing a sustainable system.

- Hydropower, water supply, historical significance, barrier for exotic species, flood control, and water level control are primary factors which may favor the renovation option at a site.

- Public safety, recreation, fish habitat improvement, cost savings, and stream ecology are primary factors which may favor the removal option at a site.

- Shoreline owners on a dam reservoir may claim that dam removal will reduce their property values. The law in Minnesota is unclear regarding the obligation, if any, for a dam owner to maintain a dam for the benefit of property owners on the reservoir. In Michigan the state recently removed a dam on a trout stream. Several shoreline owners believed they lost property value as a result. They sued the state and lost. The court decided that the existence of a dam was sufficient warning to owners of property on the shoreline that the water elevation at the time they purchased the property was temporary. Minnesota Statutes section 103G.511 empowers the state to ensure that reservoir water elevations that have existed for 15 or more consecutive years are maintained for the benefit of the public. Minnesota Statutes are silent, however, on whether reservoir property owners have a similar right to maintain existing reservoir elevations in the event that the state determines dam removal would be in the public interest. There are no known court precedents on this question in Minnesota.

VI. OTHER DAM ISSUES

- **Dam Safety Law Amendments**

The DNR is proposing amendments to the dam safety statutes as part of an agency bill on water law for the 1995 legislative session. The primary change would authorize 100% state funding for removal of publicly or privately owned dams. Currently, state cost share funding is 50% for publicly owned dams and 0% for privately owned dams. Historically, funding for dam safety projects under section 103G.511 has come almost entirely from bonding appropriations. This initiative would allow the DNR to accomplish more with the same level of dam safety bonding funds, because the cost of removing a dam is generally much less than the cost of renovation. In addition, dam removal eliminates the need for future state/local expenditures for maintenance and repair.

The proposed amendments would specifically add dam "removal" as an eligible use of state cost share funds under section 103G.511, and allow state cost share funds to be spent on removing privately owned as well as publicly owned dams. Presently, the statute refers strictly to "repair and reconstruction" of publicly owned dams.

Because of the limitations in the existing statute, the DNR has had to get special legislation to fund the removal of hazardous privately owned dams at Bernings Mill, Hanover, Stockton, and Welch, and a partially failed dam owned by the City of Stewartville. Special legislation is not an effective approach in cases where quick action can prevent erosion of adjacent shoreline properties and thousands of dollars of property damages.

About 15 of the dams on the DNR's list of 25 dams that could be considered for removal are owned by local units of government. This initiative would provide an incentive to these local units to remove rather than repair these obsolete dams because it would allow the DNR to fund up to 100% of removal costs.

- **Hydropower Potential**

Most of the good hydropower sites in Minnesota have been developed. Twenty-eight of the thirty-two active hydro dams have been operating for decades. Four more sites--Byllesby Lake, Rapidan, St. Cloud, and Hastings--have been developed or restored at existing dams since 1980. The best remaining undeveloped sites with existing dams are Coon Rapids, Minnesota Falls, and Lower St. Anthony, although they are marginally feasible sites. There are many existing dams with hydropower potential, as surveyed by the St. Anthony Falls Hydraulic Laboratory in 1983. However, there has been little interest by developers in the sites listed in that survey. A major hindrance to hydropower development is the relatively low price which developers can receive for the power sold to electric utilities. Other hindrances are regulatory costs and environmental concerns with hydropower operations. It is generally not economical or environmentally feasible to build new dams for hydropower in Minnesota. In the near term (15 years) new hydropower development on rivers in Minnesota probably will not exceed 30 megawatts of capacity. New hydropower, if any, will likely consist of expanding existing river installations.

Pumped storage hydropower development may also be proposed. These installations pump water hundreds of feet in elevation to an upper reservoir during off-peak hours and release the water through turbines during peak hours. These installations have been built in other states and are typically large projects in excess of 100 megawatts.

In the 1994 legislative session a law was passed directing the state to subsidize new hydropower at 1.5 cents per kilowatt hour. This is a substantial incentive that could encourage new development at sites that are otherwise uneconomical. For example, if 8 megawatts of hydropower capacity were established at the Coon Rapids Dam and produced 37,000,000 kilowatt hours of electricity annually, this subsidy would go to the owner/ developer and would cost the state about $555,000 annually.

• Drinking Water Supply

Ensuring water supply for the City of Minneapolis is clearly the biggest drinking water supply issue involving dams. Minneapolis is dependent on Mississippi River water for its municipal supply. In June of 1988 there was great concern that flow in the Mississippi River might diminish to the point that the water intake pipes to the Minneapolis Water Works would be unable to draw water from the river. If that occurred, Minneapolis would be left with only a 24-hour normal use supply or a 48-hour restricted use supply. That near crisis in 1988 generated much attention to the purpose and operation of the Mississippi River headwaters reservoirs. Subsequently, the City of Minneapolis acted as the local sponsor of a Corps of Engineers' study of the feasibility of the headwaters reservoirs as a supplemental water supply. That study found that it would take 16 days or more for headwater's releases to reach the Twin Cities. The study also pointed out that the intake pipes to the Minneapolis Water Works are within the pool created by the Upper Lock and Dam at St. Anthony Falls, and that it is vital that the flashboards on the dam be in place in the event of an extreme low flow event on the river to help ensure the intake capacity is not threatened. The City of Minneapolis obviously has a strong interest in the future management of these Mississippi River dams from a water supply perspective.

Given the high cost and environmental impacts of impoundments, no agency is proposing major new impoundments for the purpose of water supply.

• Demand for New Dam Construction

The era of major dam construction is over due to concerns over cost effectiveness and ecosystem management. Most applications for permits to construct new dams will fall under the categories of flood control, wetland restoration, wildlife, and tailings and other waste containment dams. These would be primarily tributary and upland dams, rather than river dams.

Flood Control Dams. The DNR anticipates about five proposals a year for flood control dams in both urbanizing and rural areas.

Continued development in urbanizing areas will require new systems to handle increased stormwater runoff without exacerbating flooding or diminishing water quality. Deep water impoundments are one method of controlling peak discharges and trapping suspended materials. The larger of these type of structures will be subject to state dam safety rules.

Watershed districts, particularly in the Red River Valley and Southwestern Minnesota, continue to support large impoundments as a tool for controlling agricultural flood damages. Both regions have river valleys with steeply sloped uplands that drain onto flat lowlands that provide productive cropland. It is becoming more and more difficult to find impoundment sites in the transition zone between the uplands and lowlands that would provide cost effective flood control and not raise significant environmental concerns. This is evidenced by the fact that the Corps of Engineers has attempted to find sites in both regions on which to build new impoundments and has failed to find any feasible sites.

Wildlife Dams. Many low head structures are being built to restore, enhance, or create wetlands, largely for the purpose of increasing waterfowl production. Most of these structures fall below the height and/or storage criteria of the state dam safety rules but still require a permit from the Division of Waters if they are constructed in public waters.

Tailings and Other Waste Containment Dams

New dams and expansions will be built to contain wastes from the taconite industry, the power industry (for coal ash), and for agriculture to contain animal waste and food processing waste.

VII. POLICY RECOMMENDATIONS

A. Funding Dam Management Projects

The legislature needs to provide a sustained level of funding of approximately $1 million per year to allow the DNR to adequately:

- maintain the infrastructure of state owned dams that support lake levels and associated property values and recreational benefits;
- provide cost share grants to local units of government to help them properly maintain important local dams; and
- provide an effective incentive for local and private dam owners to remove obsolete and detrimental dams.

B. Amending Dam Safety Statutes

Authorize 100% Cost Share Funding for Dam Removal

The legislature should amend Minnesota Statutes, section 103G.511 to authorize the DNR commissioner to provide up to the full cost of removing obsolete and detrimental dams from state waters for both public and private owners. This initiative would provide an incentive for removal of obsolete dams whose continued repair is not in the public interest. It would also provide the DNR with the authority to act quickly in the event of a partial dam failure to protect adjacent properties from channel erosion.

Require a Dam Project Priority List Once Every Two Years

The legislature should amend Minnesota Statutes, Section 1036G.511, Subdivision 12, to require submission of a list of priority dam repair and removal projects once every two years instead of annually. This would eliminate the need for DNR to submit lists in non-bonding sessions.

APPENDIX A.
ECOLOGICAL IMPACTS OF DAMS ON RIVERS

Introduction

River modification cause by dams, in one form or another, is known to have occurred since about 3000 BC (*Petts* 1989). The earliest dams were probably built for irrigation, flood control and water supply (*Baxter* 1977). Worldwide, the expansion of human populations and activities has resulted in extensive damming, regulation and diversion of rivers. The number of large dams in the world increased sevenfold from 1950 to 1986, up to about 39,000. Altered ecosystems below dams and diversions are now the most prevalent stream environments on earth (*Stanford and Ward* 1979). In the endeavor to put freshwater sources to productive use and to control floodwaters and their pathways, the consequences in terms of habitat loss have been overlooked (*Gordon et al.* 1992).

An ecological context of river regulation has been recognized only in recent times. Many people think of rivers simply as water flowing through a channel. However, this narrow view does not capture the complexity and diversity of riverine systems. Riverine systems are coupled with and created by the characteristics of their watersheds (*Doppelt et al.* 1993).

An ecosystem is a biological community and the environment in which it lives (*Odum* 1954). The two function together, interacting so that both change. The key components of ecological integrity for river systems are: 1) natural flow regimes and natural inputs of large organic debris (wood); 2) spatially complex riparian corridors; 3) large scale diversity and connectivity between habitat units; and, 4) refugia from harsh physical and chemical conditions (*Isaac Schlosser*, personal communication).

Impacts to river systems can be categorized as simplification or loss of habitats, disruptions to the hydrologic regime, changes in water quality and nutrient cycling, interruptions to sediment transport, separation of the river from its riparian corridor and valley, and, introduction of barriers between habitats (aquatic and terrestrial). All these physical disruptions will occur to some degree under any existing or proposed dam and can have drastic impacts on the biological community in and around the stream. Elements of these topics are discussed below with examples to illustrate specific impacts.

Differences between Streams and Reservoirs

When a stream is dammed, the impoundment provides a very different habitat from that provided by the stream. Dams create areas of standing water behind them. As a result, the nutrient cycling, sediment load, temperature and oxygen regime can be very different from the river (running water) that flows into the impoundment. Also, the energy budget (source and movement of energy through) of a river ecosystem is vastly different from that of a lake or impoundment ecosystem. The communities of standing waters rely for the most part on photosynthesis as a source of energy. In streams, the ultimate energy source is allochthonous (introduced material). In terms of living resources, running waters are physiologically richer than still waters and river organisms have evolved various adaptations enabling them to take advantage of the benefits conferred by the current. Consequently, a different aquatic community is created by a dam. Because floating organisms are being swept away by the current continually, the population of plankton is low in streams, whereas the benthic (bottom-dwelling) population may be high. The benthic organisms of streams often display body shape adaptations for life in flowing water that are unnecessary and ill-fit to standing water environments. Therefore, the impoundment favors plankton, aquatic insects and fish species that are more suited to the standing water habitat created by a dam.

Changes caused by Dams - Velocity and Discharge

Current is a major factor controlling the distribution and abundance of most stream organisms (*Hynes* 1970). Impoundments invariably modify both flow patterns and discharge (*Ward* 1976). This can lead to changes in current speed and substrate, water temperature, and oxygen (discussed below). Impoundments may modify the flow regime in five major ways: 1) reduce mean annual runoff, 2) reduce seasonal flow variability, 3) alter the timing of peak flows, 4) reduce flood flows, and 5) impose unnatural flow pulses (Ward and Stanford 1987). An example that illustrates the impacts of velocity and discharge alteration on stream biota is a hydropower facility that "peaks" or pulses water through, to maximize electric power generation. When outflows are rapidly changed, fish and aquatic insects can become stranded and die on gravel bars below the dam (see *Cushman* 1985 for a complete review of "peaking" impacts on the ecology of rivers).

Changes caused by Dams - Sediment

Free-flowing river systems exhibit characteristics of sediment transport and nutrient spiralling that help define habitat in the river and the biota that is present (*Cummins* 1979). In a free-flowing stream, nutrient inputs (e.g., leaf litter, soluble nutrients in runoff) are processed by specific biota (e.g., bacteria, insects, fish) and sequestered (bound) in biomass. When these organisms die or waste materials from feeding pass downstream, nutrients are mobilized and transported with the current until consumed by other organisms or bound in substrates. This process of suspension and sequestration of nutrients longitudinally downstream is known as nutrient spiralling. When a dam interrupts this process, the reservoir acts as a nutrient sink. That is, incoming nutrients are sequestered in reservoir organisms or bound in sediments. Because the reservoir is lake-like, a higher percentage of nutrient export will be in the form of plankton, not normally a significant component of a stream. The resulting "food" (nutrients) that leaves the reservoir is altered from what would be found in a free-flowing stream. As a consequence, the invertebrate assemblage and fish community below the dam are changed to species suited for this food source.

Changes caused by Dams - Water Quality

Water quality changes often occur by creating dams. When dams are built on a river, normal sediment transport is disrupted. Reservoirs reduce discharge velocities and cause aggradation (build up of sediments) in the channel upstream and associated tributaries limiting the quality of habitat available for fish. Over time, the reservoir fills with sediment and that stretch of river is degraded and lost. Downstream of a dam, discharged water is relatively clear and "sediment hungry." As such, the water flowing from the dam is highly erosive, and can erode the river banks below the dam, until a new sediment load equilibrium is established. Important habitats for invertebrates and fish can be lost in the process, as well as riparian habitats, farmland and manmade structures. Also, the outflow water's increased capacity to carry sediment scours the channel downstream resulting in "armoring" of the stream bed. Armoring is the development of a surface layer that is coarser than the material beneath it (*Gordon et al.* 1992). The armored area results in less diverse substrates available in the stream for invertebrate production and fish spawning habitats.

Temperature and oxygen changes in the river water may also result from dams. Thermal stratification can result in outflows from the dam that are warmer than the upstream river water, and change the animal community as a result. The modified temperature regime below dams often does not supply sufficient "thermal information" for some species (*Ward and Stanford* 1982). For example, species requiring winter chill to break egg diapause (period of suspended growth) may be eliminated by the warm-winter conditions below deep release dams. Summer cool conditions will eliminate species requiring a high absolute temperature, or the accumulation of a large number of degree days, for maturation or emergence. Shallow reservoirs act as heat traps that may increase downstream summer temperatures to the detriment of the indigenous cold water fauna (*Fraley* 1979). Suboptimal temperatures can delay development of macroinvertebrates, decrease the reproductive potential of adults, and place species at a competitive disadvantage (*Vannote and Sweeney* 1980). Both the physiology and the behavior of fish are affected by temperature and the physiological relationships with temperature are not linear (*Crisp* 1987). Quite small changes in the timing and pattern of water temperature fluctuations can have disproportionate effects on the vital processes of fish. These changes cause shifts in the aquatic community, favoring a different group of invertebrates and fish. The general pattern is for deep releases of cold reservoir water to cause a decrease in numbers of warm-water fish species (*Pfitzer* 1967). Oxygen deficits caused by the standing water environment in impoundments are widely recognized. Outflows from dams with lowered oxygen tend to favor species that are adapted to these low oxygen conditions (like carp), from the invertebrate community on up to fish. Often these species are less desirable than those in an oxygen-rich river (like trout or smallmouth bass).

Changes caused by Dams - Introduction of Barriers

Dams also reduce the ability of a river to serve as a corridor, for both terrestrial and aquatic organisms (*Ward and Stanford* 1987, *Malanson* 1993). Negative impacts occur to fish and invertebrate populations that will lose access to critical stream habitats necessary to complete some life stages. Removal of a dam allows passage of fish species throughout the river system. Fish movement is limited by dams. Eliminating fish from the reaches of a river above a dam can cause changes in the ecosystem, as other species of fish or invertebrates gain a competitive advantage or decline in their absence. Fish have a variety of habitat needs depending on discharge, physical habitat structure, associated species, and season. For example, suitable spawning habitat for a fish species may be located at a headwater site, whereas, juvenile or overwintering habitat may be located at a downstream site. If a dam interrupts migration routes, access to important habitats may not be possible. Examples of this concern are:

- species like walleye, white sucker and lake sturgeon typically move upstream during spring and early summer to suitable spawning habitat.
- smallmouth bass will move downstream in the fall to suitable overwintering refugia.

Freshwater mussels in the river systems will also benefit from the removal of a dam. The larval form of mussels are known as glochidia. They are obligate parasites that are dependant on fish for nourishment until transformed to the juvenile life stage. At this time, the juvenile stage releases from the host fish for colonization of the stream bottom. Because fish would benefit from access to all reaches of a river network, mussels would gain advantage from increased exposure to hosts for attachment and movement to suitable habitats for colonization.

Overview

Ecologists now view rivers both as systems with their own characteristics and as connectors of land, air and water through space and time (*Dynesius and Nilsson* 1994). Ecological interactions are now understood in both directions, between the river and the receiving sea, the main river channel and its tributaries, the rivers source (headwaters) and its mouth, the river and its terrestrial surroundings, the river and the atmosphere, and even the river and the hyporheic water (that is, water moving underground). A new appreciation for the ecological connectivity between channel, hyporheic and floodplain attributes of a river needs to occur if river ecosystems, especially those involving large floodplain components, are to be adequately protected or rehabilitated (*Stanford and Ward* 1993). To preserve our river ecosystems, we must recognize and maintain their four dimensional nature: the longitudinal, headwater to mouth dimension; the horizontal dimension, where exchanges of matter and energy occur between the channel and river floodplain; the vertical dimension, as defined by interactions between the channel and connected groundwaters; and the fourth dimension, time, which superimposes a "through time" hierarchy on the three spatial dimensions (*Ward* 1989). When dams are imposed on river systems, a wide array of changes will occur that affect the stream ecology as well as the property and infrastructure of society. Careful evaluation of these impacts is necessary before a dam is built, repaired or removed.

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