LONG TERM EFFECTS OF AN INTERBASIN DIVERSION ON THE MILK RIVER

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ABSTRACT

Diversion of flow from the St. Mary River into the Milk River Basin commenced in 1917 and has had a pronounced effect on the receiving channel. The impact of this diverison on the morphology of the Milk River was assessed by comparing historical surveys and air photographs and analyzing available hydrologic and suspended sediment data. The major effects of the diversion included channel widening, increased cutoff activity and increased sediment yield.

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INTRODUCTION

Interbasin diversion projects have been carried out in Canada for hydroelectric and irrigation development. Assessing the environmental impacts of future projects will require reliable predictions of the physical changes to the sending and receiving streams. Unfortunately, river processes are complex and only poorly understood so that the expected channel adjustments often can not be predicted analytically. However, the lack of theoretical methods may be partly overcome by using documented case histories from similar engineering projects. Examples of this approach are illustrated in the study of Kellerhals et al. (1979) where eleven major interbasin diversions were investigated and a classification scheme was developed for evaluating their effects.

This study, a continuation of earlier work by the authors. (McLean and Beckstead, 1981), describes the impact of the St. Mary diversion into the Milk River. The project commenced in 1917 making it probably the oldest interbasin diversion in Canada. The project is unusual because an extensive channel survey was carried out in 1915 on the Milk River to monitor the impact of the diversion. Repeat surveys in 1979 and 1980 and historical air photography have provided some means of measuring the longterm channel changes along the river. This data has allowed some conclusions to be drawn on the reliability of available methods for predicting channel adjustments due to longterm changes in flow regime.

PHYSICAL SETTING

Most of the Milk River Basin consists of rolling prairie grasslands. Precipitation averages only 300-400 mm per year with about two thirds of this amount occurring between April and August. Periods of high runoff can occur in late March and April due to snow melt and between June and July due to intense localized rainstorms.

The North Milk River flows as a misfit stream along the course of a glacial meltwater channel, (Williams and Dyer, 1930). In addition, several very large abandoned coulees enter the mainstream of the Milk River below the town of Milk River (Figure 1). Downstream of Writing-on-Stone Park, the Milk River flows in a box canyon up to 1600 m wide and 150 m deep.

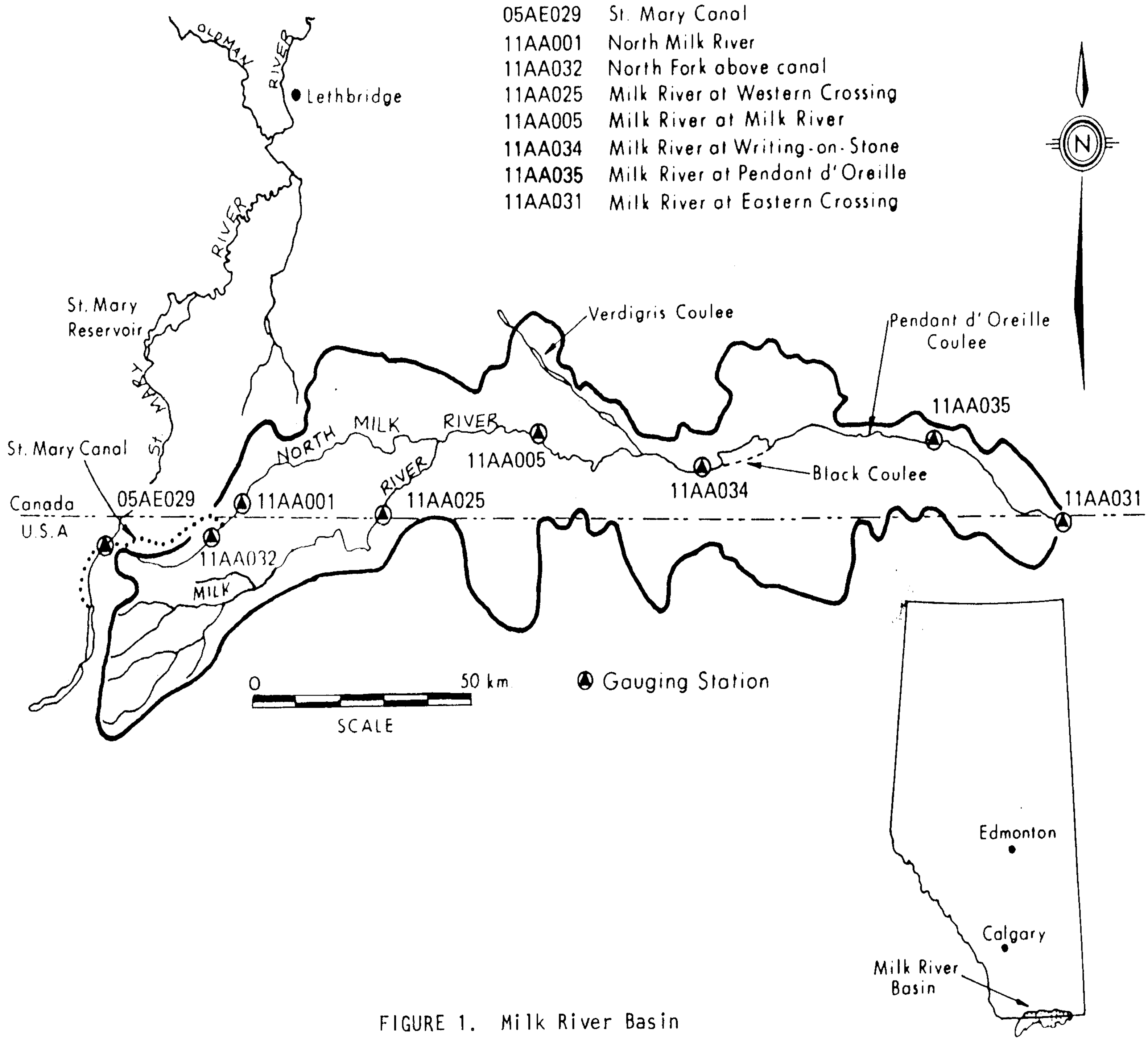

FIGURE 1. Milk River Basin

PROJECT DESCRIPTION

The St. Mary - Milk River diversion was initiated as part of the Boundary Waters Treaty of 1909 between the United States and Canada. Water from the St. Mary River is conveyed by a canal to the North Milk River in Montana (Figure 1). After crossing the International Boundary the water flows 80 km before meeting the larger unregulated south branch. The combined north and south branches form the main stem Milk River which flows an additional 235 km eastwards before re-entering the United States at the Eastern Crossing.

The study area has been sub-divided into four major reaches:

- the regulated portion of the North Milk River
- the unregulated south branch
- the regulated Upper Milk River from the North Milk River confluence to Writing-on-Stone Park
- the regulated Lower Milk River which extends to the Eastern Crossing on the Alberta-Montana border.

Some of the physical characteristics of these reaches are summarized in Table 1.

Due to a combination of erodible valley wall deposits, lack of vegetation and the occurrence of hydraulic piping in the canyon walls, extensive area of badlands have developed along the Lower Milk River. These areas contribute large quantities of sand and silt sized sediments to the river (Barendregt and Ongley, 1979).

AVAILABLE DATA

The earliest surveys of the river are the legal surveys of 1898-1906 (Alberta) and 1906 (Montana). In 1909, F.H. Peters, Chief Hydrographer, Dept. of the Interior, established seven hydrometric stations along the North Milk and Milk River (Figure 1) and made estimates of bankfull channel geometry and discharge capacity (Peters, 1910). The hydrometric stations on the North Milk River (11AA001), at Milk River town (11AA005) and at the Eastern Crossing (11AA031) have been maintained over the last 70 years.

Between July 6 and November 27, 1915, Peter's crews surveyed 131 cross sections along the entire Canadian portion of the river. A detailed planimetric map was prepared showing the channel and adjacent floodplain. Bed and bank materials, vegetation and other cultural features were frequently noted.

The first air photo survey of the river was made in 1922 and photos are available for many other years.

Repeat surveys were made in 1979 and 1980 at 20 of Peter's cross sections on the North Milk River and at 26 cross section on the Milk River. Additional surveys were made at three hydrometric stations (11AA001, 11AA034 and 11AA035) in order to provide further data on channel hydraulics and bankfull flows. Sediment samples of bed and bank materials were also collected.

BASIN HYDROLOGY

Seven longterm Water Survey of Canada gauging stations have operated along the Milk River system (Figure 1). Canal inflows from the St. Mary River have been recorded continuously since 1917 during the irrigation season. Natural flows are recorded on the North Milk River 1 km upstream of the canal outlet in Montana (gauge 11AA032). Regulated flows have been recorded on the North Milk River 11 km downstream of the canal outlet (gauge 11AA001) and at four other sites on the main Milk River (Figure 1).

The corresponding natural daily discharges were computed at these stations for the period 1917 - 1976 by subtracting the recorded daily canal inflows from the measured regulated flows:

$$Q_{i_{nat}} = Q_{i_{reg.}} - Q_{i_{meas}} \qquad [1]$$

The 60 years of daily regulated and natural flows were then analyzed at each station in order to determine the impact of the diversion on the discharge regime along the river.

The main effect of the diversion has been to maintain flows in the Milk River between 10 to 20 m^3/s between May and September, averaging near 15 m^3/s between June and August (Figure 2). By comparison, natural flows would have ranged between 1-2 m^3/s on the North Milk River and about 2-10 m^3/s on the Milk River at Eastern Crossing during this same period. As a result, the mean flow on the North Milk River has been increased by close to a factor of 20 (Figure 2).

The St. Mary River diversion has also substantially altered the frequency of floods on the North Milk River, which can be illustrated by comparing the flood frequency distributions calculated at the North Milk gauge (11AA001) located downstream of the outlet (Figure 2). It is apparent that in many dry years when rainstorm and snowmelt floods have been absent, the diversion releases govern the annual flood on the river. As a result, the mean annual flood on the North Milk River has been more than doubled by the diversion. In addition to increasing the magnitude of flood flows on the North Milk River, the diversion has substantially increased the duration of high water each year. For

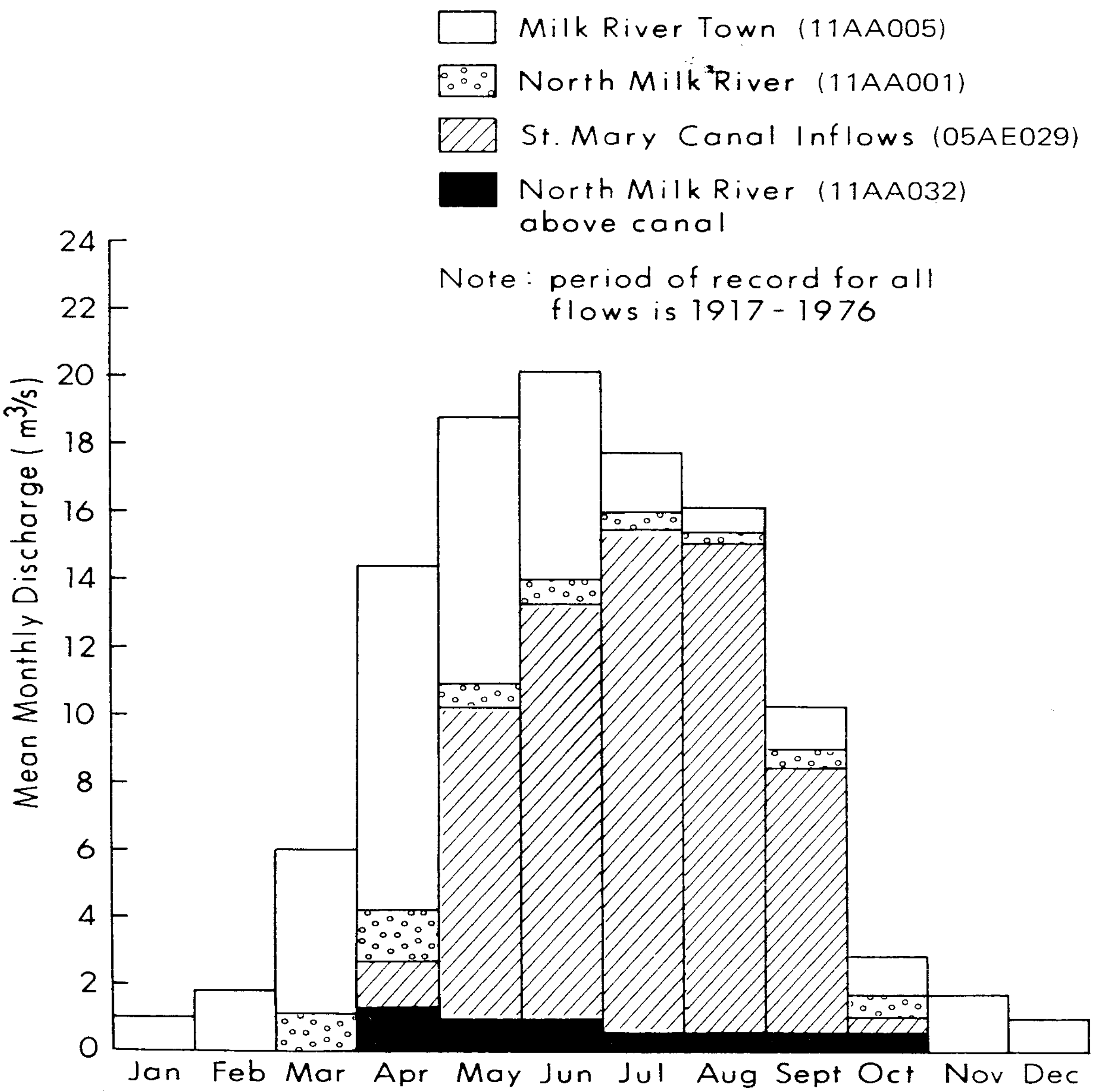

FIGURE 2a: Mean monthly flows recorded along the Milk River

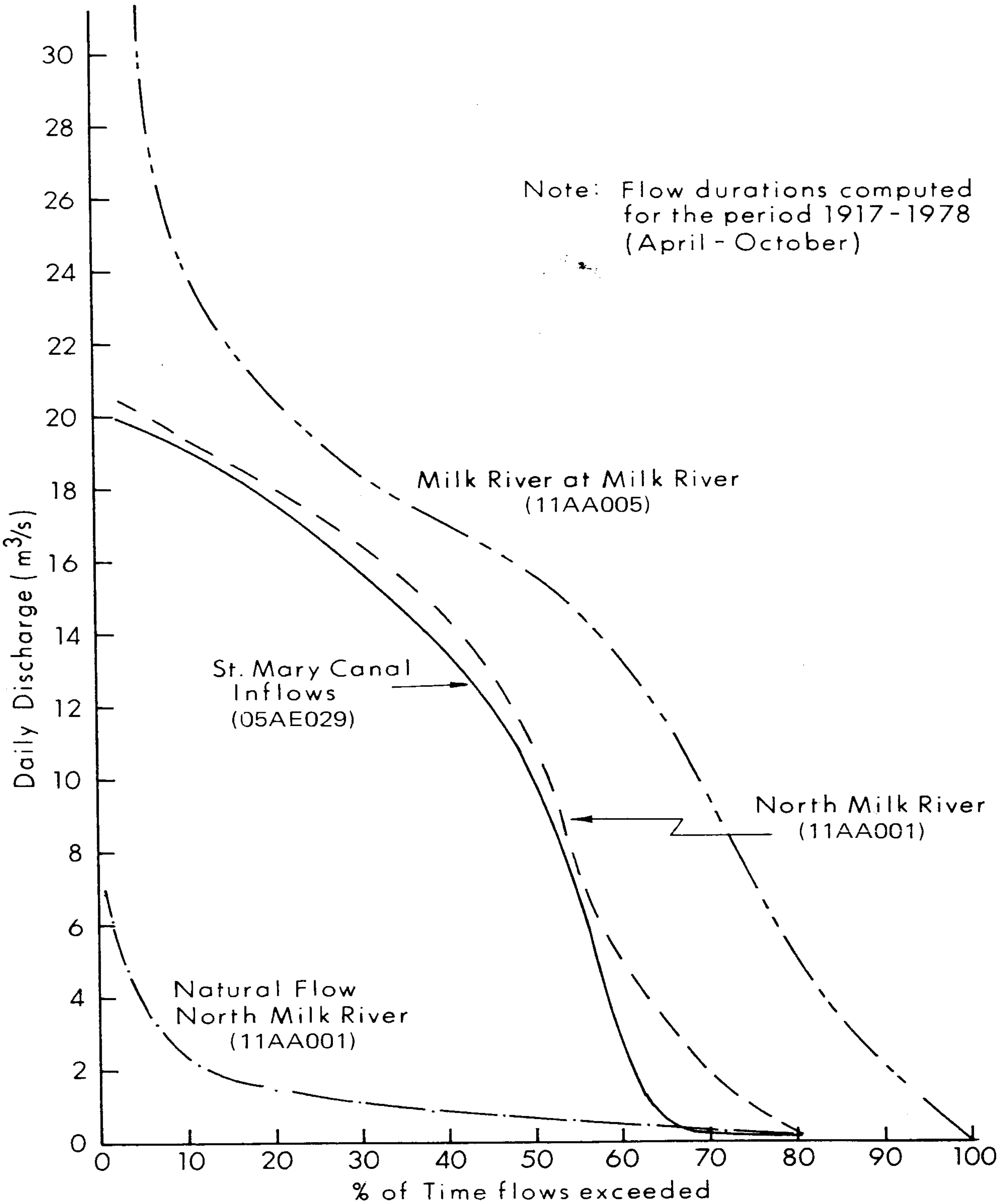

FIGURE 2b: Daily flow duration curves at Milk River gauging station

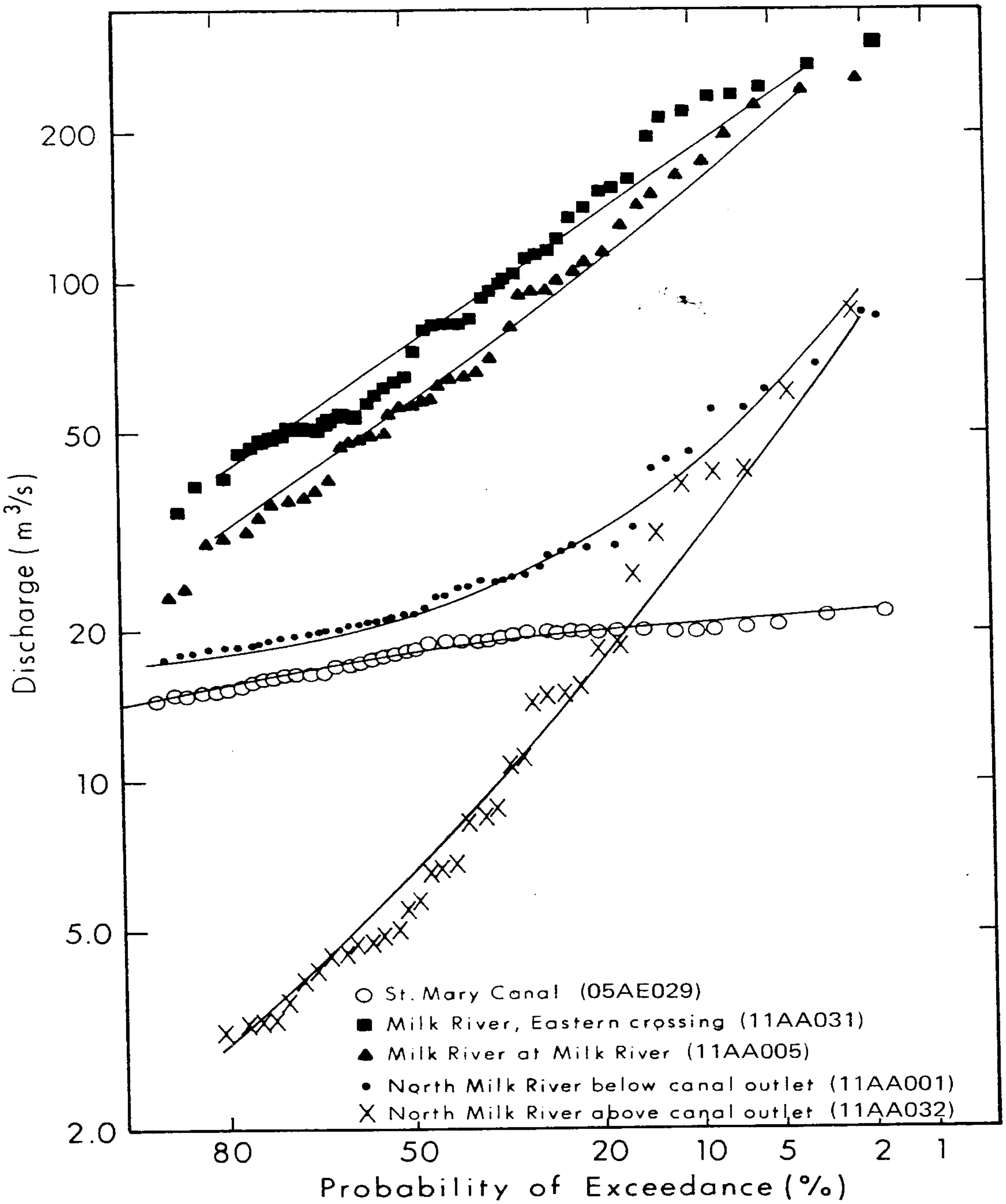

FIGURE 2c: Flood frequency curves at Milk River gauging station

example, the discharge of 15 m^3/s which has been maintained on average for three months of the year (June, July, August) would have corresponded to a 3 year flood under natural conditions. Similarly, the flow of 20 m^3/s which has been maintained on average for two weeks each year would have corresponded to about a 5 year flood in pre-diverison times. The highest flows recorded on the North Milk River have generally have been caused by rainstroms, however in many years diverison inflows have significantly increased these floods. For example, during the flood of record, roughly 20 percent was contributed by St. Mary River diversion flows.

The effect of the diversion on floods along the mainstream of the Milk River has been minor due to the much greater drainage area in this reach. The maximum recorded canal inflow of 22 m^3/s corresponds to only about 30 percent of the mean annual flood recorded at the Eastern Crossing of the Milk River (gauge 11AA031). In addition, the maximum recorded discharge at this station (300 m^3/s) was nearly 15 times greater than the largest recorded diversion flow. Therefore, although the canal has significantly increased the monthly flows along the entire river, major increases in annual floods have occurred only on the North Milk River.

PRE-DIVERSION CHANNEL CHARACTERISTICS

Prior to the diversion the North Milk River had an irregular, confined meander pattern and displayed alternating pools and riffles. The channel was composed of gravel and sand and the banks were described as predominantly sandy loam (Peters, 1910). Abandoned meander scars on the floodplain indicate that channel shifting and cutoff activity occurred prior to the diversion. Comparison of the early township surveys with Peters' maps showed five cutoffs took place, in the 15 years before the diversion started.

Based on Peters' surveys, the average bankfull width and discharge were estimated to be 23 m and 30 m^3/s respectively on the North Milk River in 1915. This discharge would have had a return period of approximately 7 years (at gauge 11AA001) under the natural flows that have occurred between 1917 - 1976.

The Upper Milk River had a meandering gravel-bed channel with silty or sandy loam banks. The channel was frequently confined by valley walls composed of stony clay or sandstone. The channel was considerably larger (bank width surveyed 52 m) than the North Milk branch due to the large drainage area contributed by the South branch (Figure 1). Peters estimated the bankfull discharge to be 48 m^3/s at Milk River town and 78 m^3/s at Writing-on-Stone Park. Our analysis of the 1915 cross-sections resulted in an average bankfull capacity of 87 m^3/s along this reach. This flow has been exceeded at least 10 times over the last 65 years which suggests the channel was not entrenched prior to the diversion project.

The Lower Milk River displayed a regular meander pattern in 1915 and contained frequent sand waves, mid-channel bars and shoals. In this sand bed reach, the average bankfull width and discharge capacity were estimated from the 1915 surveys to be 75 m and 225 m^3/s respectively. These values were found to be in close agreement to Peters' original estimates at the Eastern Crossing gauge.

IMPACTS ON NORTH MILK RIVER

The greatest impacts from the diversion occurred on the North Milk River where the magnitude and duration of floods were significantly increased. Comparison of the 1915 floodplain maps with historical air photographs and recent topographic maps showed 35 cutoffs occurred along the North Milk River after the diversion started. As a result, nearly 25% of all meanders present in 1915 have developed cutoffs. Approximately 80% occurred as neck cutoffs due to channel enlargement or progressive channel migration. The remainder occurred by irregular channel shifts or chute cutoffs. Some examples of these kinds of channel changes are shown in Figure 3.

The tendency for any particular meander bend to develop a cutoff was strongly related to the meander's geometry at the time of diversion start-up. The best indicator of meander stability was found to be the initial (1915) meander neck width (Figure 4). Approximately 80% of all meanders having neck widths greater than 40 m developed cutoffs. Many of the smaller meander bends cutoff directly as a result of channel enlargement in the first 20 years after the diversion started (Figure 4). The cutoffs on the larger meanders took place 35 to 60 years after the diversion commenced and developed as a result of progressive channel migration.

The main effect of the cutoffs has been to decrease the channel sinuosity by about 7% and to increase the overall channel slope.

Comparison of the channel cross-section surveys showed the average bankfull width on the North Milk River increased from 23 m (range 14-32 m) in 1915 to 31 m (range 23-38 m) in 1980 (Table 1). A paired t-test on the difference between channel widths showed this increase was statistically significant at $\alpha = 0.01$. The average bankfull discharge capacity of the North Milk River channel increased from 33 m^3/s in 1915 to 83 m^3/s in 1980. As a result, bankfull discharge is now exceeded only very rarely (about once in 30 years at gauge 11AA001). The increase in channel capacity resulted mainly from enlargement of the

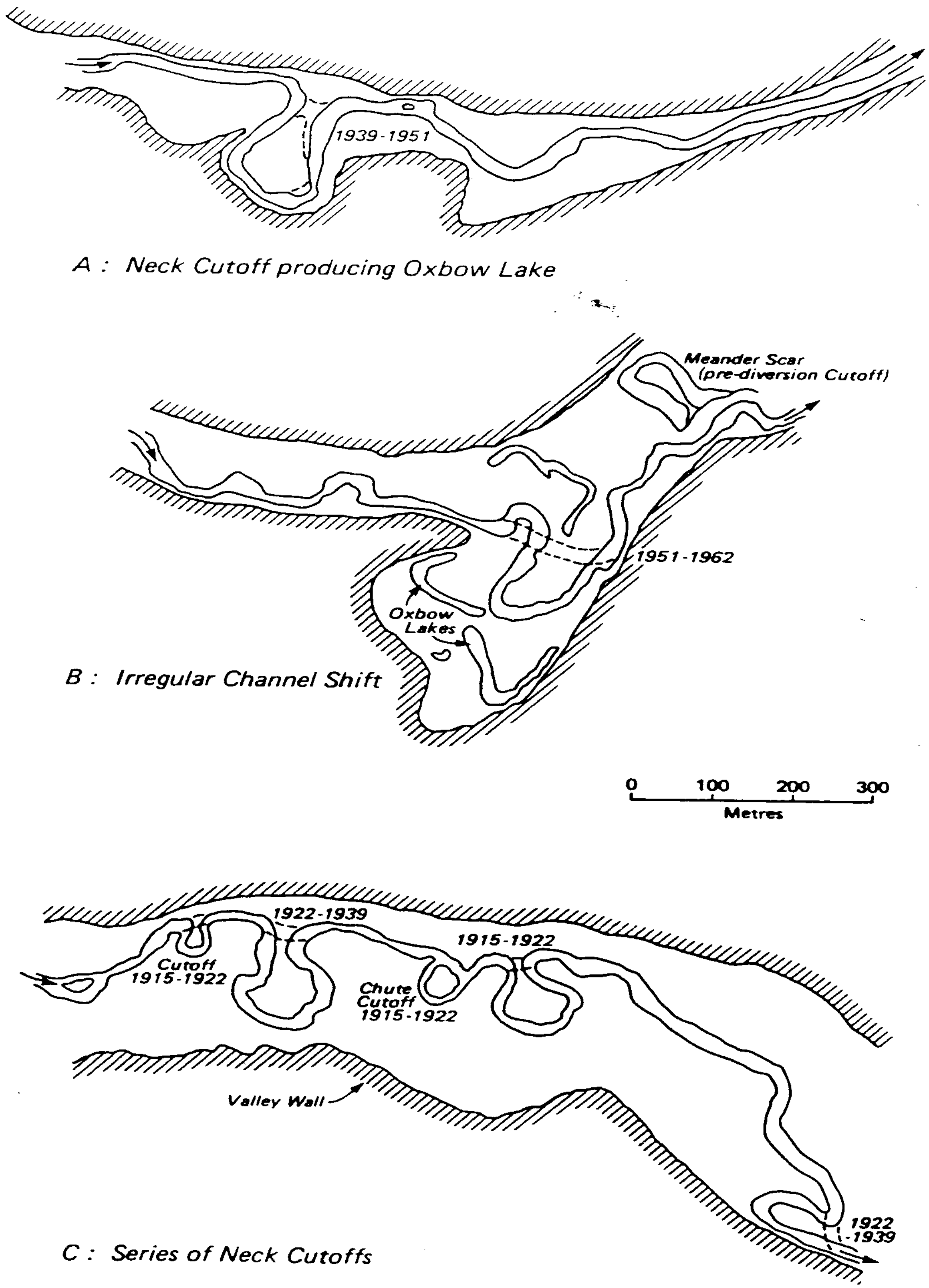

FIGURE 3. Examples of channel shifts along the North Milk River.

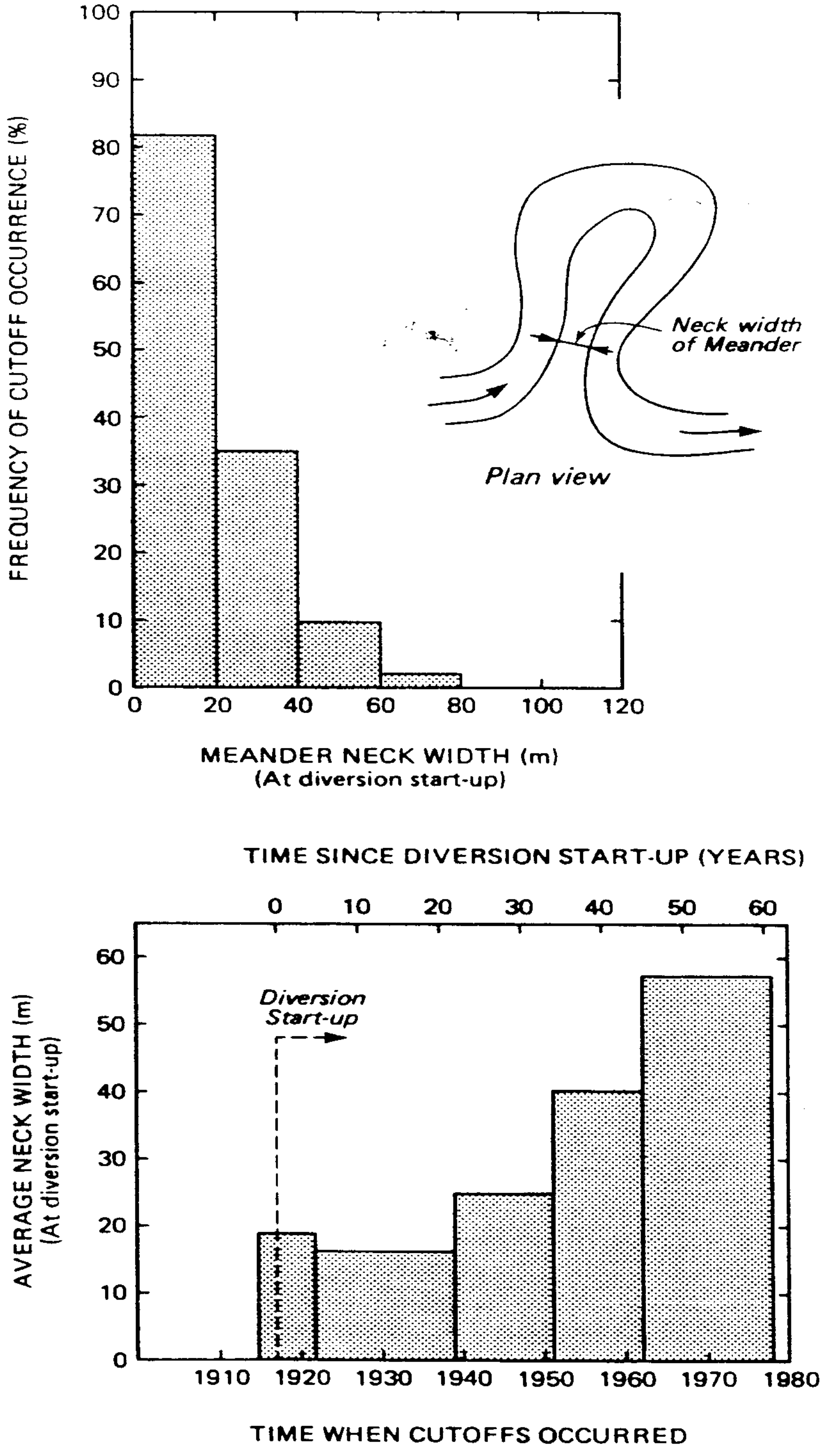

FIGURE 4. Summary of cutoff developments along the North Milk River.

channel cross-section due to widening (Figure 5). Some cross-sections indicated bankfull stage had also increased along the channel due to overbank sedimentation. Comparison of bed elevations showed that general degradation has not occurred along the river. The lack of significant degradation is probably mainly due to the presence of relatively coarse gravel sediments in the streambed. The channel bed presently has an armoured surface with a median size of about 45 mm while the median sub-surface material ranges from 15-35 mm. Critical tractive force calculations suggest the channel bed is now inactive when the discharge is less than 20 m^3/s. This flow has an annual return period of 1.5 years at gauge 11AA001 and corresponds roughly to the peak outflow from the canal.

Table 1. Comparison of Bankfull Channel Properties Surveyed in 1915 and 1980

Reach	Year	Channel A (m^2)	Area C.V.	Top W (m)	Width C.V.	Mean Depth d (m)	Bankfull Discharge (m^3/s)	Slope
North Milk River	1915	21	0.55	23	0.31	0.91	30	0.003
	1980	45	0.34	31	0.26	1.45	85	0.0035
Upper Milk River	1915	77	0.53	56	0.26	1.38	87	0.0013
	1980	81	0.34	56	0.18	1.43	81	0.0013
Lower Milk River	1915	133	0.22	75	0.27	1.78	225	0.0007
	1980	177	0.46	88	0.27	1.93	260	0.0006

C.V. = coefficient of variation (standard deviation/mean)

Figure 6 illustrates the time scales required for some of the channel changes to take place. Unfortunately, intermediate width changes between 1915 and 1980 are not known. Changes in sinuosity and cutoff activity were estimated from historical air photos, while shifts in the stage-discharge relation (specific gauge plot) at the North Milk River hydrometric station were reproduced from Kerber (1978). The specific gauge plot in Figure 6 shows that for a given discharge, the

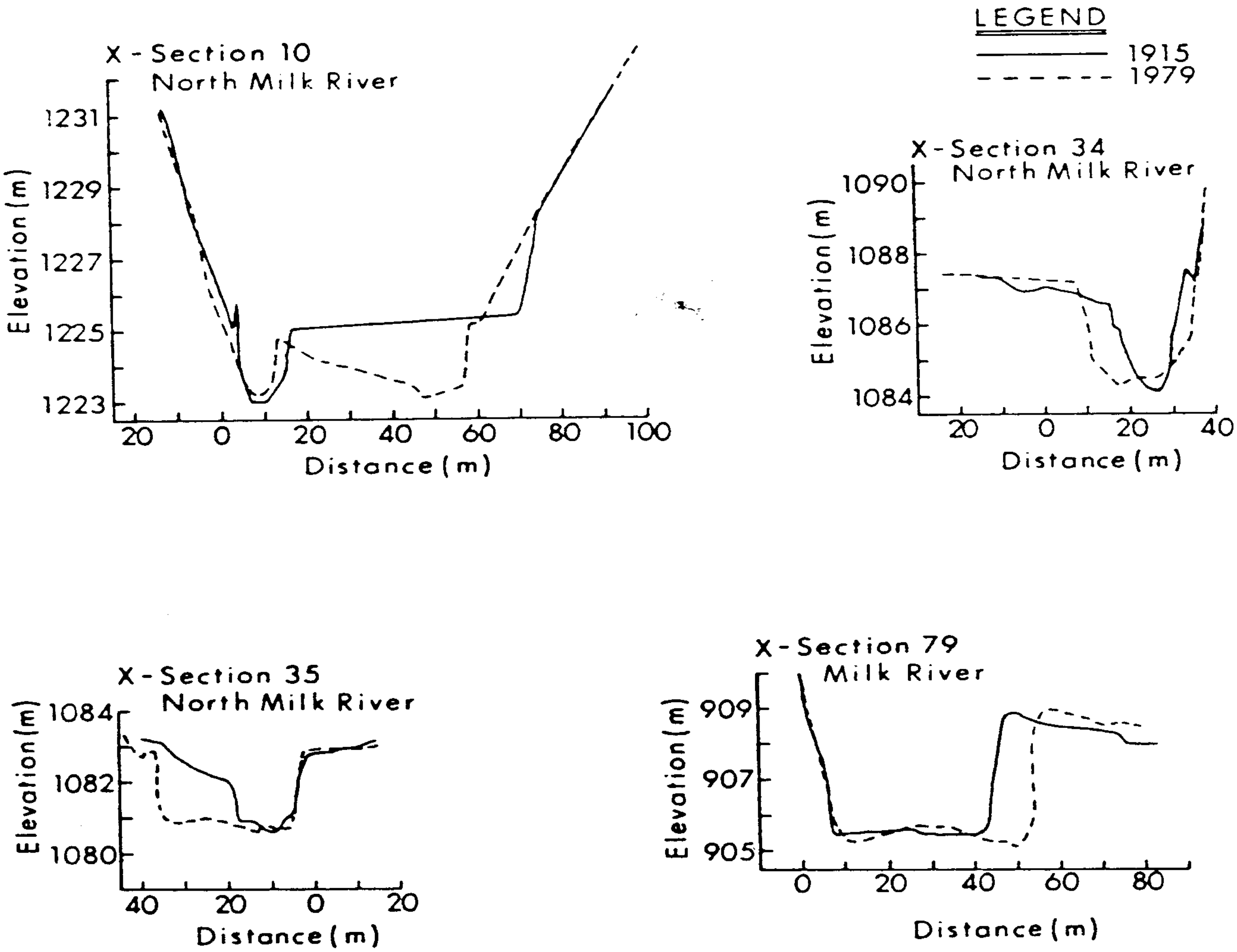

FIGURE 5. Cross-section changes on North Milk and Milk River, 1915-1979.

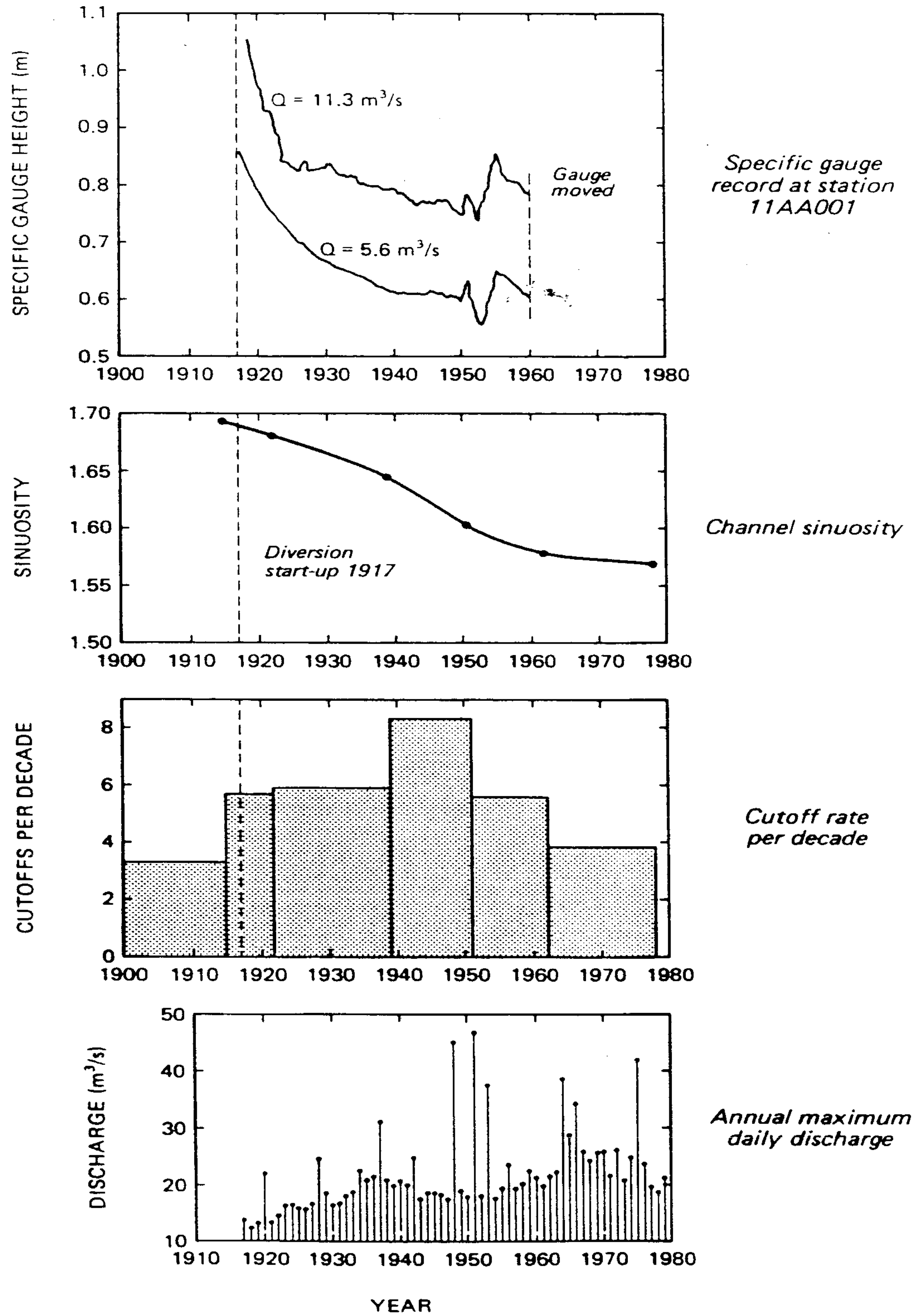

FIGURE 6. Summary of channel changes along the North Milk River.

water level at the gauge lowered systematically between 1917 and 1937. It is believed that this shift reflects the increase in the river's channel width rather than degradation.

The most active period for cutoffs and sinuosity changes occurred between 1939 and 1952, up to 35 years after the project had started. This lag time may represent the period required for the channel pattern to respond to the change in flow regime. For example, since most cutoffs developed by channel enlargment or channel migration rather than by abrupt shifts, a period of decades was required before conditions were reached where cutoffs could develop. It is expected that this lag time depended in part on the history of annual floods following the diversion start-up. If a number of large floods had occurred shortly after the diversion started, the adjustment time of the river might have been faster. In fact, the period of peak cutoff activity corresponds with the time of the flood of record on the river. Other later extreme floods in 1964 and 1975 had no significant impact on the channel pattern since, by this time, most of the short radius bends had already been destroyed.

CHANNEL CHANGES ON THE MAINSTEM MILK RIVER

Comparison of the historical air photos and maps showed no major channel pattern changes or cutoff activity occurred on the mainstem Milk River between 1915 and 1980. Furthermore, no long term channel pattern changes were observed on the unregulated South branch.

The repeat channel surveys showed no change in width occurred along the gravel bed Upper Milk River between 1915 and 1980. Some widening was measured along the sand bed Lower Milk River, although these changes were not statistically significant (at $\alpha = 0.01$). Net aggradation of approximately 0.5 m was also measured along this lower reach. A specific gauge analysis at the Eastern Crossing hydrometric station also showed evidence of net aggradation (Kerber, 1978). It is not known whether this aggradation is related to the diversion, or to the presence of Fresno Reservoir downstream in Montana or to natural processes.

IMPACT ON SEDIMENT YIELD

The Milk River was named by the American explorers Lewis and Clark on account of its high sediment concentrations during spring runoff (Holmgren, 1976). Their journal entry for May 8, 1805 states:

"The waters of the river possess a peculiar whiteness being about the colour of a cup of tea with the admixture of a tablespoon of Milk. From the colour of its waters, we called it Milk River."

The first suspended load measurements were collected in 1905 and 1906 at Havre, Montana, 85 km downstream of the Eastern Crossing near its confluence with the Missouri River (Dole and Stabler, 1909; Stabler, 1911). These pre-diversion measurements, which were collected during relatively low flows, provided an estimated sediment load of 300,000 tonnes/year. Additional suspended load measurements were collected at Havre in 1930 and 1931 to provide estimaes of sedimentation in Fresno Reservoir (U.S. Engineering Dept., 1933). These measurements indicated seasonal loads of 205,000 tonnes in 1930 and 300,000 tonnes in 1931.

Water Survey of Canada began collecting miscellaneous suspended sediment measurements in 1975 at the Eastern Crossing, at Milk River town and at the North Milk River gauge. In 1981, the sediment load (March to October) increased from 90,200 tonnes at Milk River town to over 612,300 tonnes at the Eastern Crossing. This six-fold increase in sediment load took place over a distance of 120 km and clearly reflects the contribution of the badlands along the river's lower canyon. The daily measurements showed even minor local rainstorms produced large pulses of sediment (Figure 7). These short term pulses accounted for more than 50% of the total suspended load measured in 1981.

By comparison, the repeat channel surveys between 1915 and 1980 indicated the net bank erosion along the North Milk River totalled $1.5 \times 10^6 m^3$ which corresponds to an annual sediment yield of approximately 4×10^4 tonnes/year. The total diversion discharge volume in this period was $1.12 \times 10^{10} m^3$.

Therefore, it appears the net bank erosion along the North Milk River has constituted only a small fraction (less than 10%) of the total sediment yield in the Milk River basin. The most important sediment sources in the basin appear to be situated along the lower reach of the river in the badlands.

INTERPRETATION OF RESULTS

The changes in meander pattern, channel width and bankfull capacity observed on the North Milk River are interpreted to represent the long term response of the channel to the increased discharges from the diversion. It appears the North Milk River required more than 50 years to adjust its channel pattern to the change in the discharge regime.

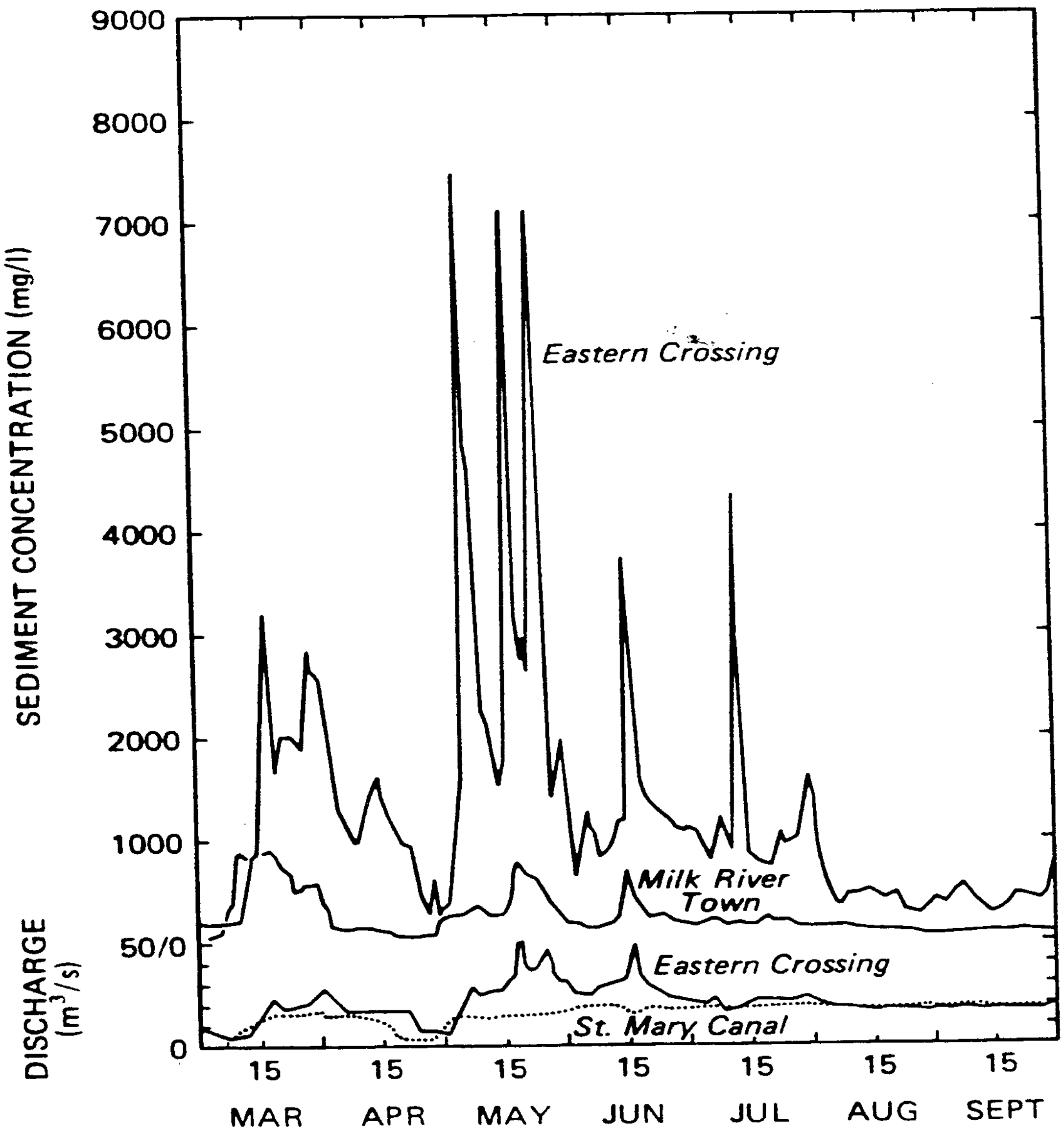

FIGURE 7. Variations in suspended sediment concentration along the Milk River in 1981.

Many other factors such as extreme floods, changes in upstream sediment supply or other engineering works could also induce changes in channel morphology. Therefore, it is obvious that natural variations in channel morphology have been superimposed on any changes induced from the diversion. It is important to consider whether these natural variations could account for the changes observed on the North Milk River. However, the relatively stable channel pattern and channel geometry observed over the last 65 years on the Upper Milk River and the South branch provide some indication that the substantial morphologic changes on the North Milk River are primarily a result of the diversion.

The diversion does not appear to have induced significant channel changes on the mainstream of the Milk River, where the canal inflows are less than 10% of the naturally occurring annual flood flows. Therefore, it appears that on the Milk River system, the morphology has been controlled by the magnitude of the flood flows (which occur only a few days each year) are not by the mean annual flow characteristics.

PREDICTING THE EFFECTS OF THE DIVERSION

F.H. Peters made a qualitative assessment on the effects of the diversion in 1910. Some of his major conclusions are as follows (Peters, 1910):

> "If this volume of water was turned into the North branch... the North Milk River would be running with banks practically full and the velocity of the stream would...create a very heavy scour. The river banks are everywhere of soft material which is liable to erosion and in a short time the river channel would adopt itself naturally to the new conditions of flow. This would mean a decided change in its average cross-section and also the river channel would change its course in many places."

Also, "the passage of this extra volume of water...would, particularly on the North branch, have the effect of enlarging the channel and would therefore lessen the tendency of the river to overflow its banks during flood."

Peters also concluded that changes on the Milk River would be less radical than on the North Milk because its channel was considerably larger.

The channel widening, increased cutoff activity and channel entrenchment that have been observed since 1915 along the North Milk River verify Peters' early predictions.

Since Peters' time, a number of semi-theoretical and empirical regime relations have been developed for predicting the hydraulic geometry of gravel-bed rivers (Bray, 1973; Parker, 1979). These equations consist of simple power functions

[2] $$X = aQ^z$$

where X is a channel parameter such as average width, mean depth or mean velocity and Q is the "dominant" or channel forming discharge. In the case of Parker's equations, X and Q are non-dimensionalized parameters which incorporate the influence of sediment size. The dominant discharge is generally considered to be a relatively frequently occurring flood with a return period of about 2.0 years (Bray, 1973). This corresponds to a discharge of 22 m^3/s on the North Milk River and is close to the maximum canal inflow (Figure 2).

An alternative approach is to use the regime equations as scaling relations which eliminates the constant in the power functions. In this form, the equation are:

[3] $$X_2/X_1 = (Q_2/Q_1)^z$$

where X_1 represents the pre-diversion channel characteristics measured at the pre-diversion dominant discharge Q_1 and X_2 represents the post-diversion channel characteristics at the new discharge Q_2. The pre-diversion 2 year flood on the North Milk River was estimated to be about 10 m^3/s.

The measured and predicted hydraulic geometry of the North Milk River are summarized in Table 2. Bray's equations provided the best estimates with the predicted values being within 10% of the measurements. This close agreement is not surprising since Bray's equations were developed from studies on Alberta gravel rivers, including the Milk River at the town of Milk River.

Table 2. Comparison of Measured and Predicted Hydraulic Geometry on the North Milk River

Method	Discharge (m^3/s)	Area (m^2)	Top Width (m)	Mean Depth (m)	Mean Velocity (m/s)	Slope
1915 meas.	10	10.2	14.5	0.70	1.00	0.0030
1915 meas.	22	15.8	17.5	0.90	1.40	0.0030
1980 meas.	22	18.3	27.0	0.68	1.20	0.0035
Bray	22		24.2	0.74	1.22	0.0036
Parker	22		20.6	0.57	1.71	0.0046

Note: 2 year annual flood (natural flow) = 10 m^3/s
2 year annual flood (regulated flow) = 22 m^3/s)

Therefore, these regime equations appear to provide reasonably reliable estimates of the long term change in average channel geometry. However, the relations do not provide any estimate of the time period required for the channel changes to occur.

It would be much more difficult to predict the cutoff activity and changes in channel pattern that have occurred along the North Milk River. An assessment of these changes would still be based primarily on interpretive skills and a general understanding of river geomorphology. The problem is complicated by the fact that the channel is often confined by non-alluvial deposits such as glacial till and bedrock. As a result, rates of bank erosion would be very difficult to predict and very variable along the river. It should be pointed out that one-dimensional mathematical models such as the sediment routing program HEC-6 do not consider any lateral channel processes such as bank erosion or meandering. However, planform changes were the dominant channel response on the North Milk River. Therefore, such mathematical models would not be very useful for predicting the impacts from a diversion project.

CONCLUSIONS

The St. Mary diversion induced substantial channel enlargment and cutoff activity on the North Milk River. The greatest cutoff activity occurred up to 35 years after the diversion started. This interval could be interpreted as the time required for the channel pattern to respond to the change in flow regime.

Some of the average cross-sectional changes observed on the North Milk River could have been predicted quite closely from simple empirical regime methods. However, the cutoff activity and time period required for channel changes to occur could not have been predicted at the present time. Present-day one-dimentional mathematical models would not have provided very useful predictions since most channel changes involved adjustments to the river's planform.

The results of this study reinforce the conclusion of Kellerhals et al. (1979) that there is a need to collect systematic long term observations of river channel changes following the construction of major river engineering projects. Such observations could improve our predictive capabilities by providing useful case histories and empirical experience. In addition, long term measurements of channel changes will be necessary to verify and calibrate future mathematical models if they ever become available. The pioneering work of F.H. Peters deserves recognition because he clearly foresaw the need for such studies.

For future projects, more attention should be given to the design of long term monitoring programs. In particular, future study programs should be designed to distinguish changes induced by the project from the naturally occurring channel changes that may occur over many decades. This will involve conducting additional surveys on the unregulated portions of the river or on nearby unregulated streams. This "paired watershed" approach was described by Church (1981) and was used to investigate the impact of the Kemano River diversion in British Columbia.

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