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EFFECTS OF DIVERSIONS
ON RIVER REGIME

by

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ABSTRACT

A review has been made of literature related to physical effects of river diversion, in particular the effects on river regime. The possible effects of diversions on the receiving and donor streams are discussed and methods which are presently available for predicting some of these effects are briefly outlined. Research needs which are required to produce satisfactory prediction methods are discussed.

A list of annotated bibliography of diversion-related literature is included with this report.

RESUME

On a effectué une étude des ouvrages portant sur les effets physiques de la dérivation des cours d'eau, surtout ceux qui en influencent le régime. On discute des effets éventuels de la dérivation sur les cours d'eau récepteurs et donateurs et on décrit brièvement les méthodes qui permettent actuellement d'en prévoir certains. On traite également des recherches requises pour élaborer des méthodes de prévision satisfaisantes.

Une bibliographie explicative des ouvrages traitant de la dérivation est annexée au présent rapport.

MANAGEMENT PRESPECTIVE

Diversion of water from a river has physical repercussions which in turn have chemical, biological and socio economic effects. Accurate appraisal of the environmental repercussion of diversions is essential to assess alternatives, and to evaluate projects.

This report provides a succinct and clear review of the effects of diversions and identifies the research requirements to reduce uncertainties for planning.

Diversions are a possible solution to water shortage and may in some cases be the only solution which is feasible. For example, diversions from the Great Lakes system are seen by some as the obvious solution to water shortages developing in the central U.S.A. Also, inequality of supply in the prairies may demand diversion. Climatic change may intensify the need to consider water transfer to offset diminishing supplies. For these reasons, a consistent research project to understand and predict the impact of diversions on river systems is justifiable. Research ideas outlined in this report should be implemented.

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PERSPECTIVE-GESTION

La dérivation d'un cours d'eau se répercute sur les facteurs physiques qui, a leur tour, ont une incidence chimique, biologique, et socio-économique. Il est essentiel de mesurer avec exactitude la répercussion environnementale de la dérivation pour pouvoir évaluer les solutions éventuelles et les projets.

Le présent rapport offre une étude courte et précise des effets de la dérivation et fait état des recherches devant être effectuées pour réduire les doutes concernant les prévisions.

La dérivation peut permettre de remédier aux pénuries d'eau et, parfois, elle constitue la seule solution possible. Par exemple, certains estiment, pour éliminer les pénuries d'eau au centre des Etats-Unis, qu'il faut de toute évidence pratiquer des dérivations depuis le réseau des Grands Lacs. Par ailleurs, la dérivation peut être nécessaire dans le cas de l'approvisionnement irrégulier en eau dans les Prairies. Les changements climatiques peuvent renforcer le besoin d'envisager le transbordement par eau pour contrebalancer l'épuisement des réserves.

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INTRODUCTION

A river diversion is the artificial movement of water by canal, pipeline or other means from its natural route into another channel or basin. The demand for diversions arises for a variety of reasons. Hydroelectric power development has been the main driving force behind a majority of the existing diversions in Canada. Demands also come from the need for stable water supplies for irrigation and for industrial and domestic consumption in areas where water is scarce. Diversions have also been created for the purpose of flood control. Major diversion projects exist all across Canada, as shown in Fig. 1.

There are many ways in which diversions can be created. A diversion canal can be used to channel the flow from one river into another. Water can be pumped from one river across a divide into a river in another basin. A river or lake can be impounded to raise the water level so that water can flow via a diversion canal across a divide. Regardless of the scheme which is used to divert the flow, physical changes will take place both in the donor stream and in the receiving stream. These physical changes will, in turn, affect the wildlife, fisheries and water quality, with accompanying social and economic impacts. Therefore, before the environmental impacts of river diversions can be properly assessed, it is necessary to be able to evaluate the effects of diversions on river regime.

This report discusses some of the possible effects of diversions on river regime and briefly outlines the methods which are available at present for predicting some of these effects. There are certain questions which cannot be answered satisfactorily with the present state of knowledge and research needs are suggested. A list of annotated bibliography accompanies this report. It is not meant to be a comprehensive listing of diversion related literature. However, most of the published articles related to diversion effects on river regime, which are actually few in number, have been included.

EFFECTS ON RIVER MORPHOLOGY

Background   Rivers are continually evolving because of the processes of erosion and transport of sediment. However, engineers are primarily concerned with the changes over a relatively short time scale (less than one hundred years). In this context, rivers are considered to flow in channels which may vary locally with space and time but display somewhat constant geometric characteristics over an extended reach. Such rivers are said to be in regime or graded (3, 21, 27)*. The morphology of a river is primarily governed by the water discharge and the sediment supply (27). The size and slope of the channel and other morphological features respond to those two variables until an equilibrium is attained. When water is diverted to or from a stream, the delicate balance is disturbed and the river responds by changing to a new slope and a new channel geometry. The exact nature of such changes is not completely defined at present but there is enough knowledge on morphological relationships to allow some qualitative predictions to be made (12, 13, 17, 18, 20, 26, 27, 29, 40).

Possible Diversion Schemes   There are many possible schemes for diverting water from the donor stream to the receiving stream. Many of these schemes involve the creation of reservoirs or impoundments. This report considers three schemes which cover the most probable situations and these are shown schematically in Fig. 2. Reservoir A in Fig. 2 represents an impoundment created in the donor stream in which the water level is set so that water can be transferred either to streams in the same basin or across a divide into streams in another basin.

In scheme number 1, the water is diverted via a canal from reservoir A to reservoir B on the receiving stream for controlled release.

In scheme number 2, water is transferred from reservoir A directly to the receiving stream instead of into a reservoir.

* Numbers within the brackets denote reference numbers

In scheme number 3, water is transferred directly from one stream to the other without the presence of a reservoir in either stream.

The possible effects of these diversion schemes on the morphology of the receiving and donor streams as well as the associated effects on lakes and impoundments in the project are to be discussed in the following sections.

Effects on Receiving Streams Throughout this report, it will be assumed that the rivers involved have reached their regime or equilibrium conditions prior to the diversion project. This assumption is necessary in order to make the discussions generally applicable.

Referring to the three schemes in Fig. 2, there is only one essential difference as far as the receiving stream is concerned. In scheme 1, a controlled rate of discharge, which usually tends to reduce the flood peak but raise the mean daily flow, is released to the river downstream from reservoir B whereas in schemes 2 and 3, the diversion discharge is added to the river's natural flow.

In the case of water released from reservoir B as in scheme 1, the downstream channel will experience a drastic reduction in sediment supply because the reservoir will trap practically all the incoming sediment except the very fine wash load. However, the river's sediment carrying capacity has actually been increased because of the increased discharge. Therefore the flow will adjust by eroding the river bed downstream of the dam. This degradation will progress to some control point downstream such as another dam or a rocky ledge, etc., until the bed slope has decreased to a new value which is compatible with the flow rate and bed material (Fig. 3). Because of the increased discharge the flow depth will likely also increase. This will depend on the bed roughness which will change because the sorting of the sediment will tend to leave the bed with coarser material than before and because the change in flow condition will change the shape and size of the bedforms. The channel will also tend to widen because of the increased flow. The sinuosity of the river, defined as the ratio of channel length to down valley distance (20), will likely change and the wavelengths of the meanders will probably increase.

The effects on the main channel will also be felt by the tributaries. As the main channel degrades, the tributaries will be undercut because the drop in the main channel stage will establish a new base level for the tributaries (Fig. 4). The slope at the confluences will be increased and this may lead to a significant increase in flow velocities as well as bank and bed erosion. The tributaries will also degrade, starting at the confluences and progressing upstream. However, it must be kept in mind that the main channel and the tributaries act as a system towards establishing a new overall equilibrium. As the tributaries are degrading, the resulting increase in sediment discharge entering the main channel will tend to offset the sediment deficiency created by the reservoir, thereby attenuating the degradation in the main channel.

Lakes along the diversion route may have their outlets eroded by the increased flow and subsequent lowering or even draining of the lakes has been documented (11).

The geomorphic effects described above are the kind of changes that will likely take place over the long term. These effects will of course be tempered by local conditions. For example, layers of bedrock or hard clay may halt the degradation and steep valley walls may halt the tendency to meander.

Before the river channel can react completely to the new flow conditions there are likely to be more immediate effects which may also have serious consequences. Initially the existing channel will not be large enough to handle the increased discharge with the result that the flood plain may be submerged for quite some time. Wetlands adjacent to lakes may be completely innundated. These can cause considerable damage to property and ecology.

The ice conditions in the receiving stream will very likely also be affected although it is not possible to generalize on the effects of diverison on the ice regime. Even though increased ice production and thus potential for ice jamming have been reported (11) ice formation and breakup are very dependent on the flow hydrograph as well as channel characteristics (2) and each case has to be considered separately.

The possible effects on the receiving stream downstream of a reservoir are summarized in Table 1. Many of the effects described in this chapter have been documented in a report of case histories of diversions (11).

In scheme 1 described above, the receiving reservoir releases a regulated flow of sediment-free water to the river downstream. This regulated flow will have a larger mean flow than before but may have the flood peaks attenuated. In schemes 2 and 3, the receiving stream still carries its natural water and sediment discharge but receives an additional inflow of sediment-free water from an artificial tributary, i.e., the diversion canal. Downstream of the diversion point, the river has increased its sediment carrying capacity because of the increased flow. It will therefore attempt to make up the sediment deficiency by degrading the bed and at the same time lowering the bed slope. This process will progress downstream as in scheme 1, although the degradation will be less severe because the natural sediment load has not been halted. However, because there is no dam to act as a barrier, the degradation initiates a complementary response in the river upstream of the diversion point. The degradation downstream establishes a new base level and leads to an increase in bed slope in the area immediately upstream. This causes degradation of the upstream river bed and provides an increase in sediment supply to the reach below, attenuating the degradation downsteam of the diversion point. Ultimately, when equilibrium has been re-established, the river bed will have been lowered, with a flatter slope downstream of the diversion and with the upstream reach flowing at the pre-diversion slope (Fig. 5). The upstream erosion may affect lakes in the upstream reach with the possibility of channels being incised in the lake bed and partial or complete drainage of the lakes.

The effects on tributaries of the receiving stream will be similar to those of scheme 1, although to a lesser degree because the degradation in the main channel is likely to be less severe.

The overall effects for schemes 2 and 3 are also summarized in Table 1.

Table 1. Possible Effects on Receiving Stream

Downstream of Receiving Reservoir (scheme 1)	Diversion Input from Canal (schemes 2 and 3)
1. Channel degradation and lowering of channel bed.	1. Degradation upstream and downstream of diversion point but less than scheme 1.
2. Gradual flattening of bed slope until equilibrium is established.	2. Flattening of bedslope downstream of diversion point. Progressive erosion upstream until pre-vious slope is re-established.
3. Increase in depth, width and meander wavelength, change in sinuosity.	3. Increases in depth, width and and meander wavelength downstream. Change in sinuosity.
4. Head cutting and unstable banks in tribuaries.	4. Head cutting and unstable banks in tributaries.
5. Progressive upstream bed erosion in tributaries. Pre-diversion slope is re-established with lower base level.	5. Progressive upstream bed erosion in tributaries. Pre-diversion slope ultimately re-established with lower base level.
6. Partial or complete draining of lakes along diversion route or along tributaries.	6. Partial or complete draining of lakes along diversion route or along tributaries.
7. Innundation of floodplain at initial stage.	7. Initial innundation of floodplain downstream of diversion point.

Effects on Donor Streams

Referring again to the three diversion schemes considered in Fig. 2, there is no difference between schemes 1 and 2 as far as the donor stream is concerned. In both cases the reservoir releases a reduced flow, virtually free of sediment, to the downstream reach. This is in contrast to scheme 3 in which the downstream reach still receives the total sediment load carried by the river.

In the case of the reservoir release, there will be a tendency for some degradation of the downstream channel because, although the flow has been reduced, it still has a certain sediment carrying capacity. With the sediment supply cut off by the reservoir the flow will begin to erode the stream bed. The extent of the degradation and flattening of the channel slope will depend on the bed material and the new discharge. Obviously if the flow is reduced to a little trickle one would not expect much erosive action. If the flow reduction is large, a significant portion of the old river bank will be exposed. In large rivers, the undercutting of the new riverbank by wave action can lead to very rapid erosion of the banks with large quantities of sediment being added to the river (33, 34). With the reduced flow, there will likely be reduction in depth, width, as well as meander length.

Because of the lowering of the water level in the mainstream, tributaries along the route will experience undercutting and the gradual increase of the bed slope. Along the main stream, the water levels will be lowered because of the reduced flow. As a result, flood plains may no longer experience any floods and wetlands may become completely dry. The overall effects on donor streams with reservoir releases are summarized in Table 2.

When the water is diverted from the donor stream directly by canal or pipeline, as in scheme 3, the normal practice is to separate the sediment and divert clear water only (32). Therefore, downstream of the diversion point, there will be a decrease in water flow with no decrease in sediment load. As a result, sediment deposition will occur and the bed slope will gradually increase until it is steep enough for the flow to carry the whole sediment load. The extent of the aggradation will of course depend on the proportion of flow diverted and the amount of sediment supply. Upstream of the diversion point the flow rate and sediment load is unchanged but because of the downstream aggradation, there will be an increase in stage which will propagate upstream. This will lead to depositon of sediment upstream and the upstream bed level will continue to aggrade until ultimately the old regime slope has been re-established. These changes are depicted schematically in Fig. 6.

Depending on the extent of the aggradation in the donor stream there may also be significant effects on its tributaries. The base levels of the tributaries will be raised and this in turn will reduce their slopes, resulting in sediment deposition in the lower tributary reaches. The deposition will propagate upstream increasing the stage until finally the old conditions exist, with the exception of the higher base level.

As a result of the reduced discharge the channel width and meander length will decrease downstream of the diversion point while little change can be expected upstream. The rise in stage may result in higher lake levels, with innundation and deposition of sediments in the flood plains. The overall effects of this scheme are also summarized in Table 2.

Reservoirs and Impoundments

The first two schemes for diversion described in Fig. 1 both involve the creation of reservoirs with attendant morphological effects. The reservoirs may be created by building a dam on a river or by raising the outflow control of an existing lake to create an impoundment. With the addition of a reservoir in the system, there will be a backwater effect extending for some distance upstream. The sediment being carried

Table 2. Possible Effects on Donor Streams

Downstream of Donar Reservoir (Schemes 1 and 2)	Direct Diversion Transfer (Scheme 3)
1. Channel degradation and flattening of channel bed.	1. Aggradation upstream and downstream of diversion point.
2. Decreases in depth, width and meander length, change in sinuosity.	2. Rise in bed level and steepening of channel slope downtream. Progressive deposition upstream until previous slope is re-established.
3. Erosion of exposed banks by waves, wind and gullying.	3. Decrease in channel width and meander length downstream.
4. Lower base level for tributaries. Progressive upstream erosion of bed.	4. Aggradation in tributaries. Pre-diversion slope ultimately re-established with higher base level.
5. Lowering of water level in lakes along route. Possible drying of wetlands.	5. Increased stage in main stream and tributaries. Possible drowning of floodplain and wetlands.
6. Possible draining of lakes along tributaries.	

by the river, upon entering the reservoir, will settle out and create a delta-like formation which will slowly advance into the reservoir. This delta will add to the backwater effect and will induce the depositon of sediment in the channel upstream (Fig. 7). This aggradation will continue to progress upstream and cause increased flood stages. Under extreme conditions it is possible that the river may become sufficiently perched so that at some high flood rate, it may abandon the old channel and adopt a new one (32). Of course the effects of aggradation are much more pronounced when a new reservoir is being created and less so when an existing lake is impounded. Ultimately, the reservoir will be completely filled in and the upstream channel will have regained its old equilibrium slope. Depending on conditions of sediment supply and reservoir capacity, this may take from less than a hundred years to more than a thousand years.

The creation of a reservoir or an impoundment also raises the base levels of the tributary streams and the tributaries will begin to deposit sediments at their inflow points to the system. This deposition will progress upstream and in tributaries with steep slopes they may result in formation of features such as alluvial fans. Tributaries may be divided as a result and their eventual locations become uncertain.

The effect of reservoirs and lake impoundments is not limited to sediment deposition. The increases in water levels will create increases in water surface area and new shorelines whose materials may be much less stable than before. Increased erosion from wave action, undercutting and slumping of bank material may add large quantities of sediment to the impoundment and increase the turbidity of the water (9, 23).

Increases in water level as well as the diversion of most of the inflow may lead to significant changes in the thermal regime of an impounded lake (8). This may also affect the ice regime downstream of the impoundment.

The effects created by reservoirs and impoundments are summarized in Table 3.

Table 3. Possible Effects of Reservoirs and Impoundments

1. Aggradation of stream bed progressing upstream.
2. Increased stage, innundation and sedimentation of flood plain.
3. Rise in base level of tributaries, with aggradation.
4. Possible increased erosion of shoreline by wave action, undercutting and slumping.
5. Change in temperature regime, ice regime.

METHODS FOR PREDICTING DIVERSION EFFECTS ON RIVER REGIME

General

In order to assess the impacts of a diversion project on the environment, it is necessary to make quantitative predictions of the physical changes which will occur. The possible changes to the donor and receiving streams have been described in the previous chapter. For proper environmental assessment, one needs quantitative information on these changes including the dimensions (width, depth, slope) of the streams as they evolve to the final equilibrium conditions; the changes in plan form; the changes in sediment transport; the rates of aggradation and degradation; and the changes in ice jamming and mixing characteristics. Knowledge of these physical changes can then be used to predict the effects on wildlife, fisheries, water quality and social economics of the affected areas. Unfortunately, our current knowledge of river dynamics is insufficient for all the changes to be predicted well enough for proper assessments to be made. In this chapter, the prediction methods that can be used are briefly reviewed and the inadequacies of some of these methods are described.

Changes in Channel Cross Section

To predict the equilibrium river dimensions, the concept of river regime is often used. According to this concept, the river adjusts its dimensions such that it is in equilibrium for a given flow rate and sediment load. Using this concept, empirical equations were developed which express the depth, width, velocity and suspended sediment concentration at various locations along the length of a river as power functions of the flow rate (3, 18).

These equations are:

$$\begin{aligned} W &= aQ^b \\ H &= cQ^f \\ V &= kQ^m \\ \text{and} \quad C &= pQ^j \end{aligned} \tag{1}$$

in which W, H, V and C are, respectively, the width of the water surface, the average depth, the average velocity and the suspended sediment concentration; Q is the bankful discharge; and a, c, k, p, b, f, m and j are numerical constants. Note that, to maintain continuity, the sum of the exponents b, f and m should be equal to one while the product of the constants a, c and k should also be equal to one.

Many sets of river and canal data have been applied to Eq. 1 by various researchers to obtain values of the exponents. There is considerable variation in the results (24). However the value of 0.5 is often adopted by many investigators for the exponent b. From the Chezy equation, it can be deduced that for b = 1/2, the exponent f must be equal to 1/3 and m must be equal to 1/6.

Given the values of the exponents in Eq. 1, the changes in width, depth and velocity of a river due to a change in flowrate can be established as

$$\begin{aligned} \frac{\Delta W}{W_i} &= \left(\frac{Q_d}{Q_i}\right)^b - 1 \\ \frac{\Delta H}{H_i} &= \left(\frac{Q_d}{Q_i}\right)^f - 1 \\ \frac{\Delta V}{V_i} &= \left(\frac{Q_d}{Q_i}\right)^m - 1 \end{aligned} \tag{2}$$

in which Δ denotes the change and subscripts i and d refer to pre-diversion and post-diversion values. If values of the exponents obtained from a particular river are available, the accuracy of using Eq. 2 can be improved. Equations have also been developed for gravel bed rivers (4), with mean diameter of gravel as an additional variable.

Among the relationships shown in Eq. 1, the width relationship is the one most often used. For example, Tutt (36) used Lacey's equation, which is one of the most widely used width relationships in his study of the Kootenay River project. The flow depth and flow velocity can be evaluated using flow resistance relationships such as the Manning or Chezy equations if one assumes that the change in river slope is negligible. If changes in slope are not negligible, one can use computer models such as HEC-2 (37), HEC-6 (38) and MOBED (15) to predict the changes in flow depth, average velocity, sediment transport rate, variation in bed elevations and the geometry of sand waves for both steady and unsteady flow conditions. For example, Davies and Shumuk (6) used HEC-6 to predict the effect of the McGregor Diversion project. They used Lacey's equation to specify the width of the river and then used HEC-6 to predict the flow characteristics of the receiving stream.

The width relationship is an empirical one and is dimensionally non-homogeneous. Success depends on choosing the right exponent and coefficient for the particular river in question. It is not known what effect a change from naturally varying flow to a relatively constant discharge, such as that released from a reservoir, would have on the relationship. However, at the present time, an equation for the river width which is derived from physical principles is not available.

The existing models which can be used to calculate river dimensions are applicable to cohesionless material only. There is very little knowledge on the erosion and transport of a cohesive sediments and until such knowledge becomes available, one will have to rely completely on regime-type relationships.

Regime type equations such as Eq. 1 relate the dimensions of a river to the discharge when the river is in equilibrium. They provide no information on the time scale required for the development to the equilibrium conditions. Ability to predict the time required for reach equilibrium following a change is completely lacking at the present time.

Changes in River Plan Form

Information on plan form changes can be obtained from a number of studies on morphological relationships (17, 19, 22, 31). Leopold and Wolman (19), for example, plotted data of river slope against bankful discharge and found that a line can be drawn separating meandering rivers from braided rivers (Fig. 8). The equation for this line is

$$S = 0.06\ Q^{-0.44} \tag{3}$$

in which S is the slope and Q is the bankful discharge in cu. ft. per sec. It can be seen from Fig. 8 that when a stream receives a diversion flow, the increase in discharge will tend to change a meandering stream into a braided stream. However the degradation and lowering of the slope will tend to oppose the change. Therefore one would need to know the change in river slope before determining if there will be a change from one form to the other. The ultimate equilibrium slope can be obtained from models such as MOBED (15) and HEC-6 (38) or from other methods combining Shields criteria with bedload transport equations (14). This information, together with the post-diversion bankful discharge, can then be used in Fig. 8.

As the discharge and width of the receiving and donor streams change, their meander wavelengths will also change. Yalin (40) has argued that the meander wavelength, λ, should be directly proportional to the river width. An empirical equation for λ has been given in ref. (20) as

$$\lambda = 10.9\ W^{1.01} \qquad (4)$$

Other researchers have related λ to the discharge instead of the width. Dury (7) found that

$$\lambda = 30Q^{0.5} \qquad (5)$$

Ackers (1) presented empirical equations for λ which also took into account the effect of sediment size.

Note that if the width is assumed to increase as $Q^{0.5}$ as in Eq. 1, then Eq. 5 also predicts the meander wavelength to increase directly with the width.

Although it is possible to predict the changes in plan form, the time scale of these changes is not predictable with the current knowledge of river morphology.

Using the methods described, one can predict the changes in plan form in general terms. However, the exact nature of these changes, such as the amount of lateral shifting and the location of the channel, cannot be determined. Such predictions require new knowledge on processes of river meandering, bank erosion and sediment transport so that 2-dimensionsl mathematical models can be developed.

Attempts have already been made to develop computer models to predict the evolution and downstream migration of meander patterns (10, 25). However, these models are based on rather preliminary information on bank erosion and mechanics of meander formation. As new knowledge on these aspects become available, our ability to model planform changes will be greatly improved.

Reservoirs and Impoundments

As described in the previous chapter, the main effects of creating reservoirs and impoundments are the increased stage and aggradation of the river upstream, the increased erosion of the new shoreline and of course the stopping of the incoming sediment from passing through downstream.

The methods for predicting upstream aggradation and downstream degradation have already been discussed in previous sections. The erosion of new shorelines is a difficult problem to predict. The new shoreline may have a high composition of organic or glacial deposits which can be easily eroded by wave action. Large amounts of fine sediments may enter the water through slumping of the banks subsequent to undercutting by wave action. Mathematical models of beach shoreline changes are mainly based on the continuity in the longshore direction (28, 35) and are not applicable to these circumstances. At present there are no methods for quantitatively predicting the rates of the erosion described above. Sudden changes in levels from reservoir operation can also cause bank slumping and these rates are also not predictable.

All reservoirs have limited useful lives because they will ultimately be filled by sediment deposition. Prediction of the life of a reservoir is usually made by using curves of sediment yield from the basin to determine the amount of material entering a reservoir (39) together with an efficiency curve to determine the percentage of the material which the reservoir will retain (5). In general these methods are adequate because a high order of accuracy is normally not required.

RESEARCH NEEDS

From the previous chapter, it is fairly obvious that while the capability exists for some qualitative predictions of the physical changes which may be brought about by a diversion, there are many areas in which new knowledge is required before reliable quantitative predictions can be made. Ideally, there should be models which are capable of predicting the changes in river geometry and plan form as the river evolves from its pre-diversion condition to its final equilibrium form. There should be physically based theories which would allow the changes in ice conditions to be determined so that quantitative predictions of changes in flood frequency and flood stage can be made. There should be models which can be used to predict the evolution of new shorelines in lakes and reservoirs. Such models do not yet exist.

Models of river regime change may be developed by extending unsteady state models such as MOBED to include predictions of changes in width, meander length and cutoffs. Before this can be accomplished, new knowledge must be obtained in a number of areas of mobile boundary flows.These include processes such as bank erosion and undercutting, bed armouring, flow over flood plains and the erosion and transport of cohesive materials. Processes in the development of river meanders are not well understood and must be researched. New knowledge in these areas can lead to the development of physically based equations for width and plan form changes as well as equations for the sediment transport and friction factor which are applicable to graded sediments and cohesive materials. These relationships are required before the improvements in modelling capability can be achieved.

Estimating the effects of diversions on ice conditions is difficult because a general model of ice jam behaviour is not available. Most of the existing theories are based on crude assumptions because of the lack of information on ice jam phenomena. Therefore field and laboratory studies of ice jams must be carried out so that the effects of various factors causing ice jams can be quantified. This information can be used to formulate mathematical models of various aspects of ice jams which will lead up to a general model of ice jam behaviour. Given the predictions of changes in river regime, such a model can be used to predict the changes in ice conditions and in the frequency of ice related flood levels caused by diversions.

The evolution of new shorelines in lakes and reservoirs which come about as a result of water level changes caused by diversions depends greatly on the erosion and transportation of the shoreline material by wave action. At the present time, only some simple models on the evolution of sandy shorelines are available. These models are not applicable to cohesive or organic material which will often form the new shoreline. Therefore the erosion and transport of such materials must be studied before a general shoreline evolution model can be developed.

In densely populated areas such as the Great Lakes region, even fairly small changes in the water level and shoreline can have quite serious impacts and it is very important to be able to forecast the effects of any diversion projects on lake levels as accurately as possible. Therefore a model of the Great Lakes levels should be developed or existing models should be improved to include all pertinent factors such as evaporation, snowmelt, ice in interconnecting channels and the effects of changing slopes on the hydraulics of the interconnecting channels.

Improvements in mathematical models of river response rely on advances in theories and equations for sediment transport and flow friction factor. Verification of new theories will often require accurate measurements of sediment transport and especially field measurements. In this respect, there is a need for more research into methods and instruments for measuring bedload and suspended load in the field. The problem of measuring suspended sediment concentration close to the river bed is especially important.

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FIGURES

Fig. 1 LOCATION OF MAJOR EXISTING DIVERSION PROJECTS IN CANADA (FROM KELLERHALS et al (13))

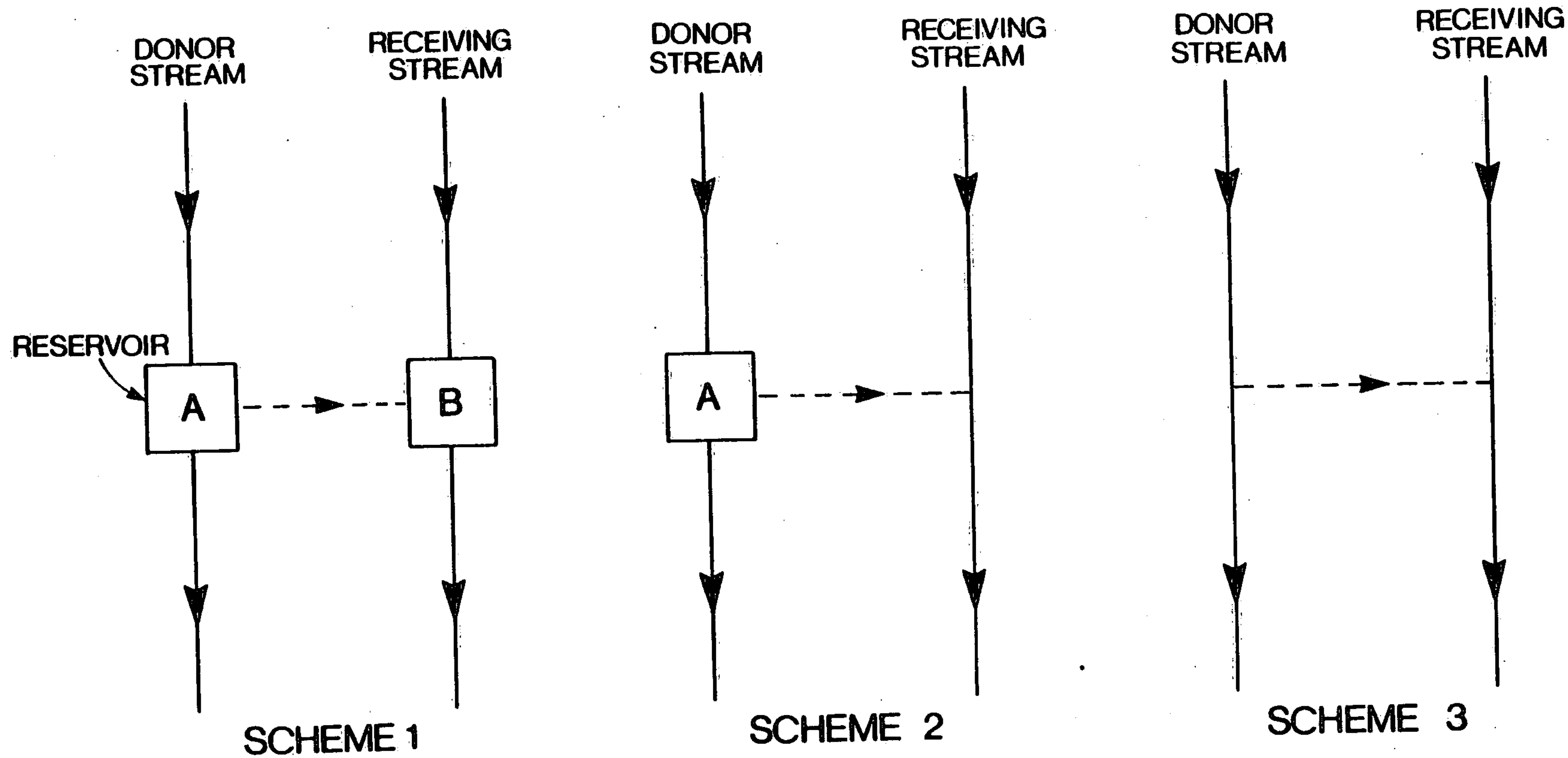

Fig. 2 THREE PROBABLE DIVERSION SCHEMES

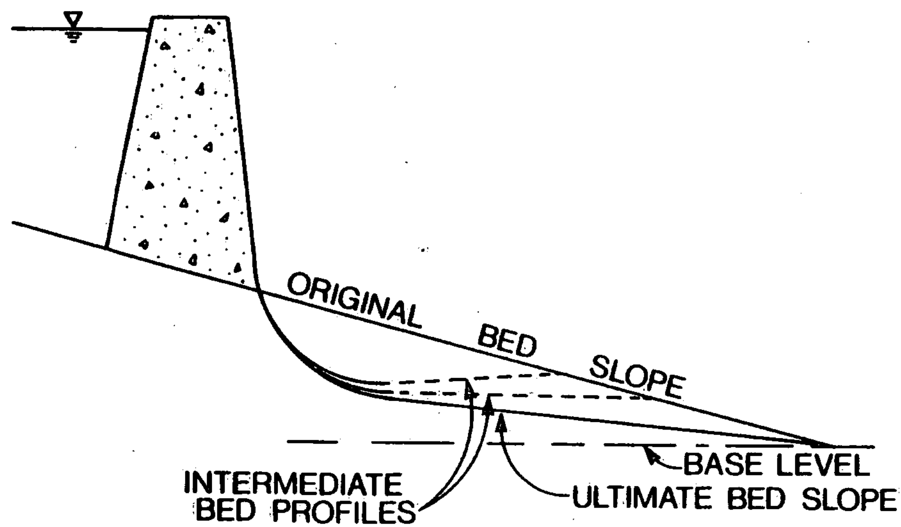

Fig. 3 DEGRADATION OF RECEIVING STREAM DOWNSTREAM OF RESERVOIR

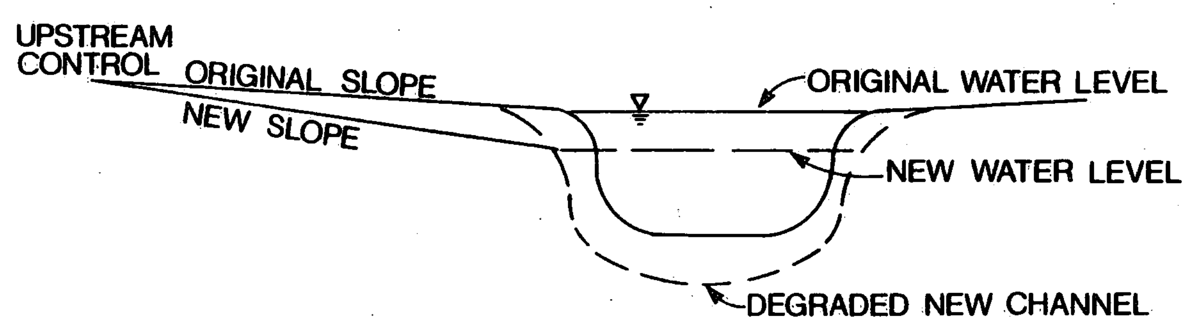

Fig. 4 TRIBUTARY EROSION

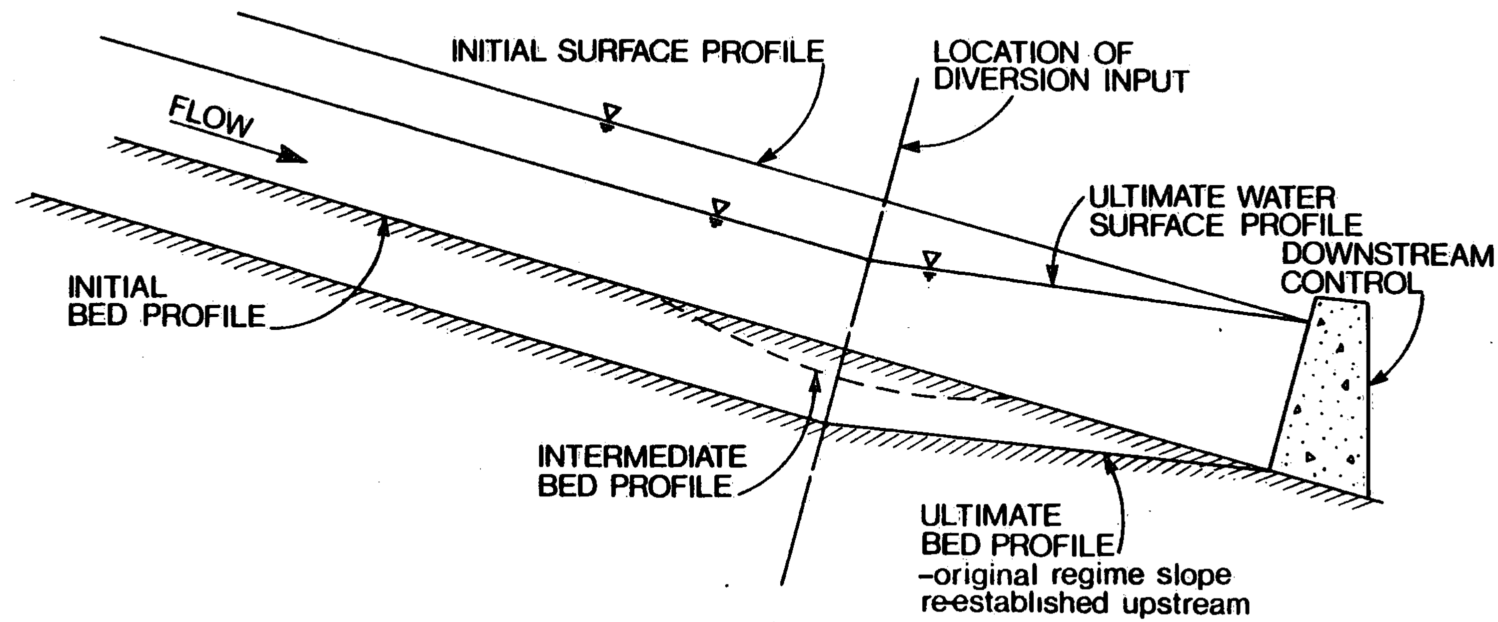

Fig. 5 EFFECTS UPSTREAM AND DOWNSTREAM OF DIVERSION CANAL INPUT

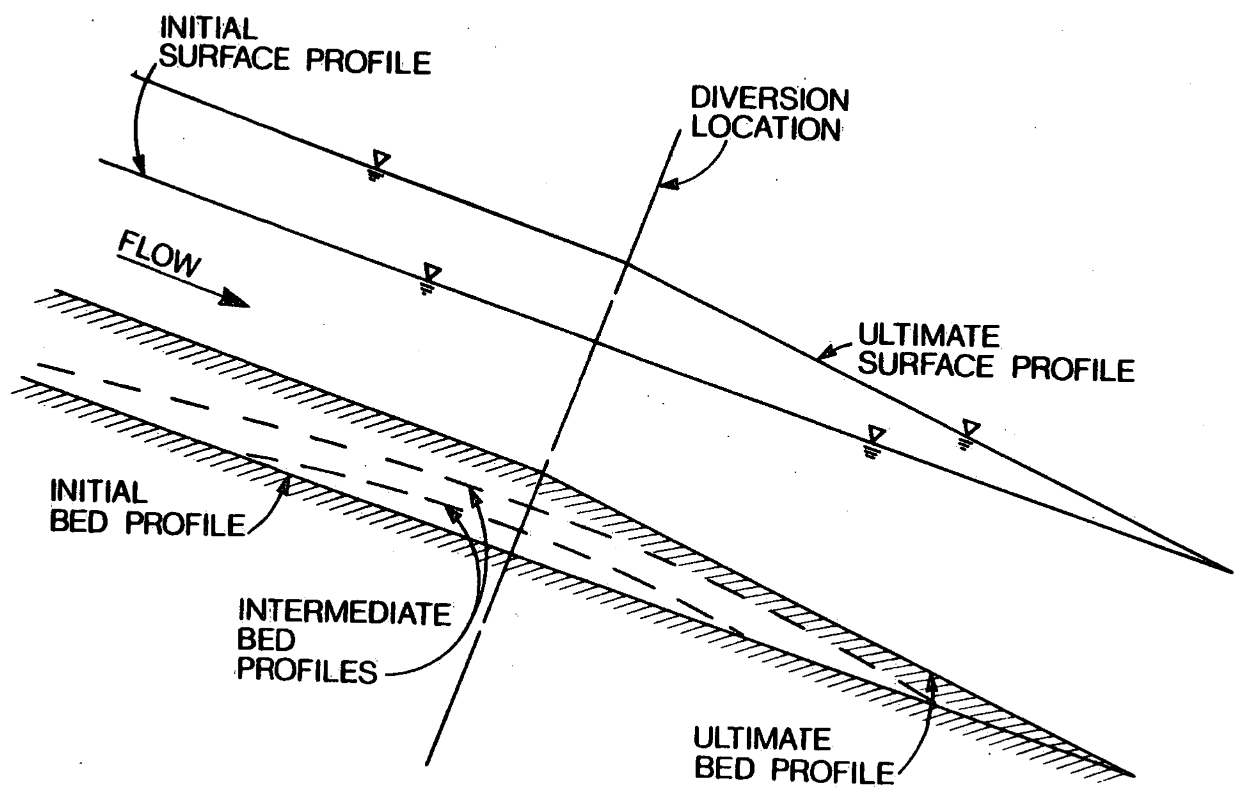

Fig. 6 EFFECTS ON DONOR STREAM – DIRECT WATER TRANSFER (SCHEME 3)

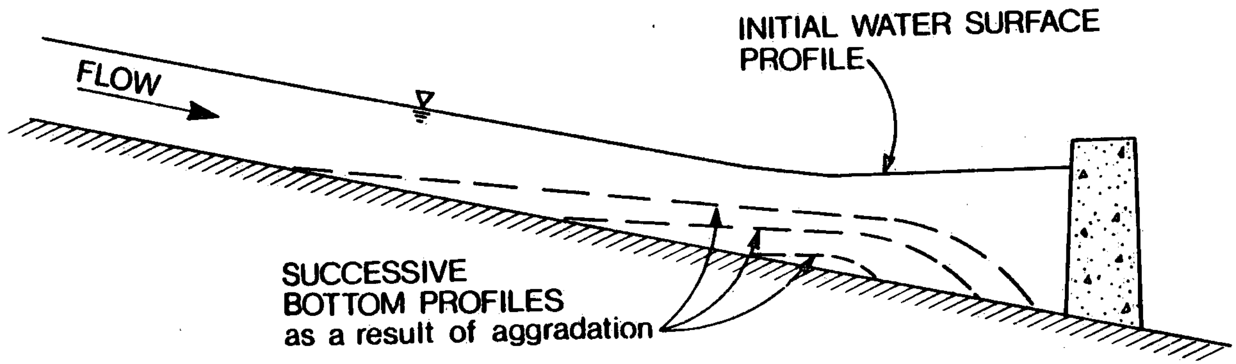

Fig. 7 CHANGES IN BED PROFILE CAUSED BY THE CREATION OF A DAM

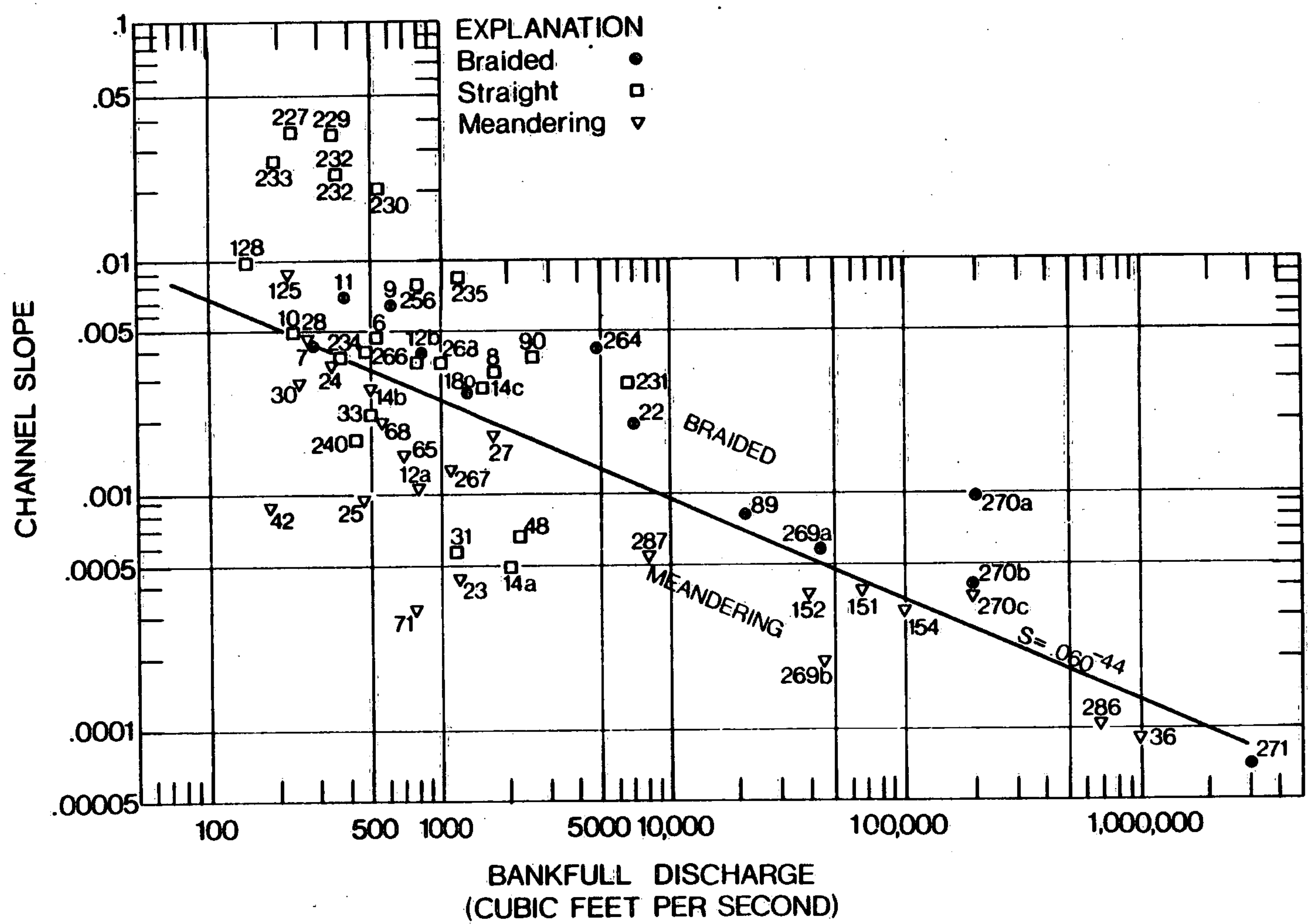

Fig. 8 SLOPE-DISCHARGE RELATIONSHIPS FOR BRAIDING OR MEANDERING IN SAND-BED STREAMS (from Leopold and Wolman (19))