IMPACT ASSESSMENT OF INSTREAM MANAGEMENT PRACTICES ON CHANNEL MORPHOLOGY

FINAL DRAFT REPORT
(Abbreviated)

TO THE

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Agency of Natural Resources
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EXECUTIVE SUMMARY

Section 1: Introduction

This Section provides the rationale for the study and an outline of study objectives. In brief this study addresses the impact on channel form associated with gravel extraction practices and associated instream works for flood hazard management. This was done through a literature review of gravel extraction case studies, the development of a conceptual model for the explanation and prediction of channel response to gravel extraction, completion of a case study in a Vermont stream and validation of the model through application to the Vermont case study. Finally these findings were used to formulate recommendations for the management of Vermont streams as a basis for further discussion.

Section 2: Literature Review

In this Section a comprehensive review of case studies pertaining to the morphological impacts of gravel extraction from numerous States as well as Europe, Africa, New Zealand and Canada is described. In total observations from 70 different river systems in 11 countries were reviewed and summarized. Morphological impacts were found to be consistent for rivers of similar form and size regardless of geographical location, climate and topography. Consequently, generalities can be made from collective assessment of case studies. In general the morphological impacts varied depending upon the location of the reach relative to the mined reach, the size of the watershed, the amount of gravel extracted relative to the supply, stream type (braided, meandering, sinuous or straight) and whether extraction practices were active or inactive. In the majority of instances flood hazard benefits were short lived and the gravel mining resulted in the de-stabilization of the channel with a commensurate increase in property loss and aesthetic and habitat degradation in both the mined reach and reaches upstream and downstream of the zone of mining. The type of mining also had a bearing on the degree of morphological impact. The stripping of gravel bars had less impact then pit mining within the river. Pit mining within the floodplain was only an issue when lateral migration of the channel resulted in capture by the pit and avulsion of the channel system.

Section 3: Conceptual Morphological Response Model

The above studies were used to formulate a model for the prediction of morphological impacts using a decision tree approach. The model represents a comprehensive and unique approach to the prediction of the response of gravel bed rivers to a disturbance affiliated with gravel extraction and associated flood hazard reduction measures. The model provides a suitable format for the development of a smart systems computer model. Such a model would provide practioners and decision makers with a systematic methodology for the prediction of the morphological impacts associated with gravel extraction and associated instream works for the reduction of flood hazard. Further, the model would be suitable for use in costing proposed mitigation works and therefore an instrumental step in the development of a prioritization algorithm for the allocation of limited resources.

Section 4: **Granville Case Study**

This Section deals with an analysis of historic aerial photographs for the White River through the Town of Granville (the "subject" channel). Photographs were available for the years of 1939, 1962, 1974 and 1995 for this region. The 1939 and 1974 photo series were subsequent to major flood flow and "maintenance" events (gravel mining and flood hazard mitigation works). The 1962 and 1995 photo series were taken 5 and 22 years after such events respectively.

The "subject" channel was subdivided into three distinct reaches: Reach 1 (upstream of the zone of mining); Reach 2 (the zone of mining from the Bowl Mill Bridge to a point downstream of the confluence of the White River and Alder Meadow Brook) and Reach 3 (downstream of the zone of mining to the first crossing of Route 100). The White River through the "subject" reach has experienced channel "maintenance" on four confirmed occasions since 1938 and possibly on a fifth occasion in the late 1920's.

The photographs were digitized and corrected for scale based on ground proofing. Morphometric parameters including the length of the thalweg, the width of the active channel, channel surface area, maximum and average normal shift were then determined for each photo year or Epoch. The same analysis was conducted for a "reference" channel. The West Branch of the Tweed River near Pittsfield was selected for this purpose because instream modifications were believed to be minimal and land use, topography, climate and watershed size were similar to that of the "subject" reach.

Pairwise comparison on the observations by Epoch indicates that the White River through the zone of mining has narrowed and straightened. Maximum and average normal shift were not determined for this reach because of the influence of maintenance activities. Downstream of the mined reach the channel has straightened and widened. Maximum normal shift has increased indicating increased lateral instability while average normal shift has declined. The later observation is consistent with channel straightening. The reach upstream of the zone of mining was not impacted because geologic controls prevent the headcutting of nickpoints and other grade discontinuities. In contrast, the Tweed River was found to relatively constant over the study period with a slight increase in width and normal shift. The morphological response of the White River is significant in comparison to the "reference" stream. The observed responses are also consistent with the observations reported from the literature review.

Section 5: Validation of The Conceptual Morphological Response Model

This Section describes the application of the conceptual model to the Granville case study. The model was applied to the three Reaches as defined in Section 4. Reach 1 showed no impact because of the step-pool form and bedrock control. Reach 2 has been subject to extensive gravel extraction and instream “maintenance” practices since the 1920's resulting in widening of the active channel and channel incisement. Large Woody Debris, large scale roughness elements (large boulders) and riparian vegetation have also been modified through the years. The model was also applied to the most downstream reach. Although some bank stabilization works are evident in this reach it is largely unmodified directly through gravel extraction practices.

Reach 2 is dominated by erosional forms resulting in Valley Formation. This process results in the formation of a new active-floodplain channel system inset within the existing system but at a lower elevation. This scenario was adequately predicted by the proposed model. The new channel has an increased flow conveyance capacity and consequently provides the intended flood hazard reduction but does so at the expense of considerable loss of property within the mined reach and the de-stabilization of the channel downstream of the zone of mining. The downstream reach is dominated by sedimentation forms leading to aggradation and the formation of chutes and cutoff channels. The formation of the bifurcation in 1998 was satisfactorily predicted by the model. Flood hazard in this lower reach initially increased as a consequence of the maintenance works. The development of the bifurcation resolved the imbalance between the elevated sediment load an the lack of stream competence by decreasing channel length and thereby increasing longitudinal slope and stream power. This interim quasi-stable form occurred with the loss of tillable farmland.

The proposed model indicates that eventual stabilization of Reach 2 and the commensurate decline in total sediment yield together with the fining of the sediment load may once again de-stabilize Reach 3. The lower reach will attempt to increase its flow length and thereby decrease its longitudinal slope to reduce its stream power to match its sediment load characteristics. It may accomplish this through increased meander development and propagation rates.

It was concluded that the proposed model provides a useful tool for the prediction of channel response to a disturbance for channel systems similar to the White River through the Granville reach. Further testing and development of the model is recommended for general application to Vermont streams.

Section 6: Flood & Erosion Hazard Management

The results of the literature review, Granville case study and the conceptual model were used to outline a general flood and erosion hazard management approach regarding instream works and gravel extraction practices in gravel bed streams in the State of Vermont. The recommendations are organized around watershed size and stream type (braided, meandering, straight) and they are intended for discussion purposes only.

In terms of watershed size channel systems of less than 38.6 mi^2 (100 km^2) were found to be very sensitive to instream works. In contrast channel systems in watersheds exceeding 386 mi^2 (1000 km^2) were found to be the least sensitive. Regarding stream type, braided channel systems were found to be the least sensitive while meander and straight channel systems were progressively more sensitive respectively. Consequently, gravel extraction in small channel systems is not recommended. Gravel extraction in moderately size watersheds may be permitted in braided systems and selected instances if a well defined management plan is followed. This may be defined using a sediment budget approach based on selected particle size fractions such that stream sediment load requirements downstream of the mined reach are satisfied. The instream programs must address issues of channel form and particle roughness, bed material gradation and structure, and the preservation of riparian vegetation and floodplain connectivity. Similarly, gravel extraction in large watersheds, particularly in braided channel systems, may be allowed in a controlled manor following completion of a well defined management plan.

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DEFINITION OF TERMS

clarification.

Active Channel: the channel that conveys flow during dry weather periods and frequent flood flow events up to the flood flow rate having a recurring interval of one occurrence on average every one and one half to two years.

Aggrade: see Aggradation.

Aggradation: the deposition of sediment in the channel raises the base elevation of the channel.

Alluvial Channel: a channel formed in sediments reworked by the stream.

Avulsion: a rapid and catastrophic shift in channel form or position.

Bank Destabilization: refers to the transformation of a stable bank configuration to one that is unstable, leading to either massive failure of the bank or slow but progressive removal of bank material. This may occur by a number of processes. One common means of bank destabilization is bank oversteepening through erosion at the bank toe, also referred to as basal scour. In this instance bank material at the base of the bank is removed through erosion by stream flow. The result is often undercutting of the upper bank leaving an overhang (the upper portion of the bank is suspended above the channel bed) or oversteepening of the bank (the slope of the bank exceeds the angle of repose).

Bankfull stage (depth): that bank height within the active channel that corresponds to the bankfull flow.

Bankfull flow: the flow responsible for formation of the active channel that just fills the active channel. This flow rate has a recurrence interval of approximately one occurrence on every one and one half to two years.

Basal Unit: the bank stratigraphic unit overlying the channel bed at approximately one third bankfull stage.

Braided: to branch and rejoin producing a netlike pattern of channels.

Capacity (sediment): stream capacity is a measure of the total mass of sediment of any given particle size that the channel can move; **(hydraulic):** stream capacity is a measure of the maximum flow rate the channel can accommodate before spilling over the top-of-bank of the lowest bank.

Competence: refers to the largest particle diameter that the stream can move at a specified flow rate (normally computed at bankfull stage).

Degrade: to downcut of lower the elevation of the channel bed (see Degradation).

Degradation: a reduction in the elevation of the channel bed through the process of scour or nickpoint migration.

Downcutting: see Degradation.

Flood Plain Channel: that portion of the stream valley inundated by less frequent or rare flood flow events, e.g., those flows that exceed the conveyance capacity of the active channel (see Active Channel).

Geomorphic Activity Rate: The rate of change of a geomorphic parameter through time. For example, channel cross-section width changes by 10 feet over a period of 10 years. The geomorphic activity rate is 1 ft/yr. In the following 10 year period channel width increased by 2 ft/year. This represents a doubling of the geomorphic activity rate.

"Hungry" Water Syndrom: Clear water is capable of entraining larger particles and moving more sediment than sediment laden water. This condition may be related to the dampening effect sediment within the water column has on the vertical component of flow turbulence. The vertical component of flow turbulence is required to provide lift on a particle and to maintain it in suspension. "Hungry" water can be created by a reservoir or the armoring of a stream wherein the sediment load been carried by the stream is reduce relative to its capacity to carry sediment.

Incised: the channel becomes entrenched deeply into the surrounding terrain and functionally separated from its flood plain such that the capacity of the active channel exceeds bankfull flow.

Incision: the process of degradation resulting in entrenchment of the active channel (see Incised).

Morphological Impacts: This term refers to changes in the form of the river; these changes could be widening caused by bank erosion, deepening caused by degradation or changes in plan form shape (see Plan form).

Nickpoint: a nickpoint is a discontinuity in bed elevation encountered by the flow as it progresses downstream. The drop may be likened to the riser on the step of a staircase. As the water flows over the riser it accelerates. The acceleration increases erosion along the riser causing it to erode in the upstream direction. The whole step moves headward or upstream. As the step moves headward the riser may get progressively smaller. Eventually the riser becomes hydraulically insignificant relative to other stream roughness elements and it ceases to migrate upstream.

Plan Form: this term refers to channel forms when viewed from the air. For example, a meandering river has a sinuous form similar to a sine curve formed by a soundwave. The amplitude, wavelength and radius of curvature of the sine curve are examples of measures of channel plan form morphology.

Scour: the process of wearing away or eroding the channel bed or banks through the action (force and abrasion) of the sediment-water mixture being conveyed by the channel.

Sinuous: curving from side to side; winding like a sine wave.

Structural Failure: refers to damage or destruction of bridges, storm sewer outlets, pipelines, etc., that are located in or along the banks or bed of the channel. This may occur either by degradation of the channel bed which undermines footings and splash pads and exposes buried pipelines or through bank de-stabilization which outflanks and exposes the bank structures, or both.

Thalweg: the line joining the deepest points on successive channel cross-sections to form a longitudinal profile of the channel bed.

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SECTION 1.0 INTRODUCTION

1.1 Background

Gravel extraction and instream works for flood hazard abatement (maintenance) have been common practice in Vermont channels up until 1985. Channel instability resulting in property loss, as well as degradation of aesthetic and habitat value lead the State of Vermont, Department of Environmental Conservation to regulate these activities through a permitting program. The permitting process significantly reduced the amount of gravel extraction and flood hazard mitigation work undertaken in Vermont channels since its inception. Proponents of continued "maintenance" argue that the lack of such work has resulted in the development of massive gravel bars within many channels. These bars deflect the flow conveyed by the channel into the banks contributing to bank failure and property loss. The influx of bank sediment also contributes to the loss of flow conveyance capacity necessary for flood hazard abatement. Record floods on June 28, 1998 lead to a renewed interest in the "maintenance" approach to channel management for flood and erosion control based on this "common sense" approach. This approach, however, ignores natural stream processes. Other alternatives have been put forward that work with the morphological tendencies of the channel system and are, consequently, more sustainable and less maintenance intensive. Proponents of the "alternative" method of channel management argue that the massive bars are a consequence of the disruption to channel processes caused by the "maintenance" activities and that the use of the term "maintenance" is itself indicative of the conflict created between the imposed and natural tendencies of the channel system. The acceleration of property loss and structural damage to bridges, roads, culverts, storm sewers and pipelines associated with gravel extraction practices is well documented. As a result of studies on the impact of gravel mining on bridge structures the US Agency of Transportation (USAoT) and the Federal Highway Administration (FHWA) will not make federal funds available for bridges damaged by such practices. Further, there is considerable debate as to the flood hazard benefits actually attained through the "maintenance" approach.

1.2 Study Objectives and Approach

A river channel forms in response to both the water and sediments generated within a watershed. A stable channel form is one in which the forces acting on the boundary are balanced with the resisting forces such that the channel is just able to move it's sediment load. When the sediment load is altered through in-stream gravel extraction practices, this balance is upset and morphological impacts often occur. As noted above, gravel mining and associated instream works for flood and erosion hazard control have been common practice in Vermont streams up until 1985. These practices have come under question because of apparent morphological impacts. The purpose of this study was to:

i) determine if morphological impacts from gravel extraction and instream works experienced in other geographic locations can be applied to Vermont conditions;

ii) develop a conceptual model for the prediction of morphological response to instream disturbances based on the findings from the literature review;
iii) examine the morphological response of a Vermont river to gravel extraction and instream maintenance practices;
iv) validate the conceptual model though application to the Vermont case study; and,
v) derive general guidelines pertinent to the management of Vermont streams based on the above findings.

1.3 River Form and Balance

A river's function is to transport water and sediment through the landscape. In all regions, humid, semi-arid, mountainous or flat, the river's function is the same. Luna Leopold wrote in "*A View of the River":*

> *"Mountains on the continental surfaces are gradually worn away by the ubiquitous weathering of their rocks, and the transport of weathered products downhill by the action of water, wind and gravity. The weathering processes that change hard rocks to erodible material incorporate water at every stage. Furthermore, water is the principal agent of movement of the weathered material that makes up the soil and supports vegetation, of the sedimentary rocks formed by the accumulation of the weathering products, and of the channels along which they are carried."*

Consequently, the primary geomorphic function of a channel is to convey sediment and water generated through weathering and hydrologic processes in the watershed within which the channel has formed. Since alluvial channels are able to adjust their boundaries the form of the channel is a product of the physical characteristics of the materials within which the channel is worn and the quantity and properties of the sediments and flows conveyed by the channel.

A stable channel form is one in which the forces tending to erode the channel boundary within which the channel is worn are just balanced by the resistance of the materials (1), such that the channel is just able to move its sediment load. Lane (1952)[1] (2) describes this balance as a proportionality between the physical characteristics and mass of sediment carried by the river and the ability of the river to perform work as measured by the product of slope and flow rate. This balance is dynamic in that vagaries in the flow and sediment inputs cause the channel to alter its morphology. The channel is considered 'stable', however, if these alterations do not represent a change in mean channel dimensions beyond a consensual range of variance over some predefined time period. A change in boundary material composition, the hydraulic characteristics of the channel or the magnitude and physical characteristics of the sediment supply to the channel represent potential disruptions to this balance.

[1] Lane, E.W. (1955). "Design of Stable Channels", American Society of Civil Engineers, transactions, 120. Pp. 1234-1279

Depending upon the magnitude of these disturbances and the sensitivity of the channel system, morphological adjustment could occur. The extraction of gravel from the river bed constitutes such an impact by altering the sediment regime. Instream works such as channel armoring, enlargement and the removal of Large Woody debris and riparian vegetation alter channel hydraulic geometry, boundary material resistance to scour and the hydraulic characteristics of the channel. These modifications may also result in morphological adjustment to the channel.

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SECTION 2.0
LITERATURE REVIEW

2.1 Methodology

This study used a two track approach to acquire information on the impacts of gravel extraction from bar scalping (or skimming), instream pit mining (dredging) and flood plain mining. An Internet and database search was complemented with phone interviews and e-mail correspondence with professionals (Appendix A-Sec 2) on the impacts of gravel extraction. The literature review focused only on morphological and flood related impacts while comments from professionals in the field were more far ranging. Summaries of the correspondences and papers reviewed as well as a detailed discussion of the key findings from the literature search are presented in Appendix A Section 2 of this report.

A table format covering key physical attributes and impacts was used to standardize the review and reporting process. Some of the studies did not contain all of the information on the physical attributes and morphological impacts outlined in the table. Never-the-less, the majority of the studies contained sufficient information to be sufficient for comparison with other studies and subsequent interpretation of the reported findings. Tables A2 to A19 in Appendix A Section 1 document the main findings from each relevant study.

The studies were divided into two categories. Those that gave watershed specific information, and those that contained overall reviews or analysis of gravel mining impacts. Tables A2 to A18 contain watershed specific information (case studies). Studies that contained only review information are cited by river in Tables A19. This method was adopted to avoid duplication of information. For example, if Chache Creek was mentioned in more than one study, it only got one listing in Tables A2 to A19.

Only information written in the studies was included in the tables. For example, personal knowledge could inform one on the climate or hydrology of the Alps or Cascades, however, if that information was not provided in the study it was not catalogued in the tables. This was done to minimize interpretation of the paper. The information in Tables A17 and A18 was provided by Mr. Randy Klein, a consulting hydrologist, for three rivers with which he was personally familiar. This information came from published and unpublished studies prepared by a professional in the field.

The literature review included an Internet and database search using the key word combinations, some of which yielded no results, listed in Table 2.1. Notes and information from interviews with professionals in the field are found in Appendix A Section 2 The phone interviews lead to Aldaron Laird, Scott McBain and Bill Trush of California and Mike Roell of Missouri. These researchers are conducting literature searches on the impacts of in-stream gravel mining for the National Marine Fisheries Service (NMFS) and the Missouri Department of Conservation. Reference lists form Larid, McBain and Trush and draft copies of Mike Roell's work were used to find applicable studies. Reference lists from these studies were used to identify other pertinent publications. Following identification of relevant publications the Vermont Department of Libraries conducted the database search to locate the publications.

Table 2.1 Summary of Key Word Combinations Used in Internet Search

Key Word Combinations	**Some Yielded Results**	**Yielded Results**
river gravel extraction/river gravel mining/stream gravel mining/geomorphology in-stream management/flooding rechannelization geomorphology/channel alteration geomorphology/river gravel dredging/stream channel enlargement/stream Channel geometry alterations stream blockage removal/river debris removal	•	
gravel extraction/debris removal/gravel mining/river debris/stream blockage/blockage removal/stream channel geometry/stream channel enlargement/gravel dredging/geomorphology channel/rechannelization stream mining/gravel mining and streams/stream management		•

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2.2 Summary of Case Studies and General Observations

Data from a review of case studies in the literature included observations from 70 rivers in 10 different States within the U.S.A. as well as observations in seven other countries around the world. The countries other than the United States include:

1) Austria
2) Canada
3) England
4) France
5) Japan
6) Kenya
7) New Zealand

The review papers included many of these case studies and other data including data collected in Taiwan. This assessment focuses on the case studies. Physical data describing the case study watersheds, their approximate size and location, are summarized in Table 2.2. The case studies represents a good cross-section of watershed sizes, geographical locations, stream types (braided, meandering, etc.) and climatic regimes.

In summarizing and interpreting the case studies some discrepancies may occur due to differences in the definition of terms used by the various researchers. Despite this potential problem the literature review demonstrates that rivers in Europe, Japan, Africa, New Zealand as well as Alaska and the continental United States (despite widely varying climate, topography, surficial geology and other basin characteristics), typically exhibit similar morphological responses to in-stream gravel mining. These impacts vary with:

a) the location of the subject channel segment relative to the mined reach, i.e. upstream of the mined reach; downstream of the mined reach; and, within the mined reach;
b) the magnitude of the disturbance making the impacts scale dependent;
c) the method and history of extraction, i.e. current (active) or historic (inactive); and,
d) other intervening factors such as geologic controls, changes in land use and flow control structures.

Table 2.2 Summary of Rivers Cited in the Literature as Case Studies on the Morphological Impacts of Gravel Extraction Practices

Ref.	River	Location	CDA (mi^2)	Ref.	River	Location	CDA (mi^2)
46, 14, 7	Skykomish	Washington	535	42	Naugatuck	Connecticut	307
74	Mad	Vermont	139	74	White	Vermont	18
74	Trout	Vermont		74	Browns	Vermont	92
70, 61	Puyallup, White & Carbon	Washington	1000	54	Clackamas	Vancouver	
59	Middle Arve	France	766	43	Crooked	Arkansas	462
39	Lower Mississippi			80	Lower Mackenzie, Stony Ck	Oregon, California	741
4	Illinois King & Crooked Ck	Arkansas	672, 530, 300	15(a)	Amite, Tanoa, Boque Chitto, Buttahatchee, Tombigbee	Mississippi, Lousianna	
17, 7	Dry Ck	California	217	79	Salzach	Austria	
58	Griffre	France	125	7	Lower Manawata	New Zealand	2300
19	7 Small Basins	Alaska	<39	65	Athi, Thwake, Keiti & Muooni	Kenya	
19	13 Medium Basins	Alaska	39 to 386	12, 12(a),7	Russian	California	1484
19	5 Large Basins	Alaska	>386	8	Redwood Ck	California	278
27	Amite	Louisiana	772	3	Little Bighorn	Oregon	239
7	Humptulips Wynoochee	Oregon			Lower Eel	California	3113
7	Cache	California	1150	68	Wooler	England	20.3
67, 80, 5	Tujunga Wash	California	115		Water		
	Mad	California	485		Lower Van Duzen	California	426

CDA is the Catchment Drainage Area,
Reference (Ref.) numbers refer to the citations provided in Reference section.

A summary of the main findings from the review of these case studies is provided in Table 2.3.

The above morphological impacts have been observed with all types of gravel mining including scraping, in-stream pits and flood plain pits. Although avulsion was more evident when instream pits were used or when a floodplain pits captured the channel flow, this specific form of adjustment was not commonly reported. On a more general note, gravel mining tends to:

i) cause the mined reach of the channel system to become incised; and,
ii) initially reduce the supply of coarse material to the downstream reach.

These initial impacts de-stabilize the channel system followed by a myriad of adjustments as the channel attempts to find a new balance between sediment load, boundary erodability and the forces exerted on the boundary. The adjustment process may either be discontinuous but generally progressive or catastrophic. Once a reach has become incised its flow conveyance capacity increases and it is more susceptible to bank erosion and property loss during high flow events and catastrophic failure during rare flood flow events. Flood damage and bank erosion also result in damage to or premature failure of riparian structures such as bridges, fords, storm-sewer outlets and pipelines. The US Agency of Transportation (USAoT) and the Federal Highway Administration (FHWA) have documented negative impacts to bridges caused by degradation associated with in-stream mining. As a result, federal funds are not available for bridges damaged by gravel mining.

The following sub-sections provides a general description of the impacts of gravel mining for the three relative segments as noted above.

2.2.1 Common Impacts Within The Mined Reach

Common initial impacts of in-stream gravel extraction within the zone of mining include:

A. incision (disconnection of the active channel and its floodplain);
B. bank collapse;
C. channel widening;
D. degradation (deepening of the bed);
E. channel straightening; and,
F. a decline in sinuosity.

The exceptions to these general findings appears to be related to the type of channel system and the magnitude of the extraction relative to the supply of material. Channel systems that were initially braided became narrower and single thread systems as incisement occurred if extraction exceeded supply. Another possible variant is related to whether gravel extraction is active or inactive and the degree of instability within the upstream channel segment. If gravel extraction is inactive and large quantities of sediment are entering the channel through adjustment processes in the upstream channel segment, then aggradation can occur within the mined reach. Where the longitudinal slope in the mined reach is sufficiently steep to pass the increased sediment load on to the downstream segment, downcutting may continue within the mined reach until other negative feedback mechanisms arrest this process.

Table 2.3. Summary of Impacts Of Gravel Mining From Literature Review of Case Studies

River (Ref.)	Location & CDA (mi^2)	Impact u/s of Mined Reach	Impact d/s of Mined Reach	Impact Within Mined Reach	Extraction History
Mad (74)	Vermont (139)			W↑, Ins, Deg,	1986
White (74)	Vermont (≈18)	Geol	Agg, W↑	W↑, Ins, $Q_{CAP}>Q_{MF}$	1998
Trout (74)	Vermont			Ins, Deg, W↑	1997
Browns (74)	Vermont (92)		Agg	W↑, Deg	1980's
Skykomish (46,14,7)	Washington (535 & 1780)			W↑, Agg, Bra, Shifting	Active since 1961
Naugatuck (42)	Connecticut (307 mi^2)	Bar↓, Geol	W↑, Bar↓	Γ↓, W↑, Deg	1980
Puyallup, White & Carbon (61)	Washington (1,000)			Ins, Agg (limited reaches)	Active
Salmon Ck, Clackamas (54)	British Columbia, Oregon (n/a)	Hcut		Ins, Deg, S↑, Γ↓, Str, Avul	N/r
Middle Arve (59)	France (766)			initially W↑,then Deg, Ins, Bra→Single Thread, W↓	Active
Crooked (43)	Arkansas (462)	Hcut, W:d↑	Agg, ϕ↑, W:d↑	Ins, W↑, ϕ↓, W:d↑	1969
Lower Mississippi (39)	N/r (N/r)		Chutes, ϕ↓, Multiple Channels	W↑, ϕ↓	Active
Amite, Taniphahoa, Boque Chitto, Buttahatchee, Tombigbee (15a)	Louisiana (N/r)	Hcut		Γ↓, Ins, W↑, S↑, Mea→Str	Active
Illinois, King & Crooked (4)	Arkansas (300, 672 & 530)		W↑	W↑, Hom, PoolL↓ (2 of 3), PoolL↑ (1 of 3)	N/r
Salzach (79)	Austria			Ins, Deg, AL→RC, W↓, Bra→Single Thread, ϕ↑	Active

Table 2.3. Contd.

River (Ref.)	**Location & CDA (mi^2)**	**Impact u/s of Mined Reach**	**Impact d/s of Mined Reach**	**Impact Within Mined Reach**	**Years Since Extraction**
Dry Ck (17, 7)	California (217)	Hcut, AL→RB		W↑, ΔS=0, Deg, Ins, W:d↑, d↑	N/r (dam u/s 1950)
Russian (12, 12a,, 7)	California (1483)		Deg, W↑	Ins, W↑, Deg, S↑, d↑, Bars↑, Γ↓, Win, d_P:d_R↓, α↓ Q_{ACT}>Q_{BFL}	Active
Stony Ck (25)	California (741)	Bra→Ins, ξ↑, W↑	ϕ↓, W↓, Ins, Deg, Γ↑	Bra-Single Thread, Deg, initially W↓ now W↓, Ins,	Active
Wooler, Water (68)	England (20.3)	Hcut		Ins, Deg, Initially W↑ Currently W↓, ξ↑,	1979
Little Bighorn (3)	Montana (239)		Agg, Γ↓, W↑	Deg, Q_{CAP}>Q_{BFL}, S↑, Γ↓, W↑	1987 (53% of main stem channelized)
Mad (Klein, 1999)	California (485)	Hcut	Ins, Deg, ϕ↓, Ar↓, W↑, ξ↑, α↓	Deg, W↑, d↑, Nrif↓, RifL↑	Still active
Lower Van Duzen (Klein , 1999)	California (426)			Deg, ξ↑, W↑, α↓, d↑	Still active
Lower Eel (Klein pers comm, 1999)	California (3113)			Deg, W↑, ξ↑, α↓, d↑	Still active
Griffre (58)	France (125)	Hcut	Deg	Ins, Deg→Agg (after mining stopped), W↑ Bra→Step Pool, Str, Low Gradient	Aggrading areas still mined
Athi, Thwake, Kaiti, Muooni (65)	Kenya (N/r)		Agg	Ins, Deg, W↑ (except Muooni ΔW=0)	Still active (extraction exceeds supply)
7 basins (19)	Alaska (<38.6)	Hcut, Deg (4 of 7), ξ↑, P↑	ϕ↓, Ar↓ (5 of 7)↓, P↑, Agg, d_{AVE}↓	W↑ & S↑ (5 of 7), v↓, Bra↑, d_{AVE}↓	1986-1996
13 basins (19)	Alaska (38.6 to 386)	Hcut (1 of 13), Deg (8 of 13), W↑, P↑ (1 of 13)	ϕ↓ (4 of 13), d_{AVE}↓, W↑, Agg	d_{AVE}↓, W↑, W:d↑, Q_S↑ & S↑ (8 of 13)	1996-1979

Table 2.3. Contd.

River (Ref.)	Location & CDA (mi^2)	Impact u/s of Mined Reach	Impact d/s of Mined Reach	Impact Within Mined Reach	Years Since Extraction
5 basins (19)	Alaska (>386)	Hcut (2 of 5), Deg (1 of 5)	Agg, $d_{AVE}\downarrow$	$Q_S\uparrow$, W↑, W:d↑,$Q_S\uparrow$ & S↑ (1 of 5), Agg, d↓	1997-1986
Redwood Ck (8)	California (278)	Hcut, Deg		Ins, Deg, Bars↓, W:d↑, Hom, Γ↓	Active since 1987
Amite (27)	Louisiana (772)	W:d↑	Deg initiated, W:d↑, Ar↓	Mea→Bra, Γ↓, Ctf, W:d↑	N/r (massive quantities extracted)
Humptulips & Wynoochee (7)	Oregon (N/r)			Ins, Deg, ΔW=0	N/r (Extraction exceeds supply)
Lower Manawata (7)	New England	Γ↑, ϕ↑	Γ↑,ϕ↓	Deg	Active
Cache Ck (7)	California (1150)	Nkp↑, Deg	Bra, Shifting	Ins, Deg, W↓, $Q_{CAP}>Q_{MF}$	Active
Lower Mackenzie (80)	Oregon (N/r)	Deg	Deg	Ins	N/r
Tujunga Wash (67, 80, 5)	California (115)	Nkpt↑, Deg, W↑		Ins, W↑, Deg, d_P:$d_R\downarrow$	N/r

Legend

Agg=Aggrading
AL=Alluvial
Ar↓= armor decreasing
Ar↑= armor increasing
Avul=Avulsion
Bar↑=increase in bar formation
Bar↓= erosion of bar forms
Bra=Braided
Bra↑=Increase in braiding
CDA=Catchment Drainage Area
Cf= meander cutoff
d↓ = decrease in channel depth
d↑= increase in channel depth
Deg=degrading
d_{AVE}=average channel depth
d_P:d_R↓=loss of pool riffle definition
Hcut=Headcutting
Geol=Geologic Control
Hom=Homogenization of bed material
Ins=Incised
Q_{BFL}= flow with RI=1.5 years
Q_{INS}=flood of inset channel
Q_{CAP}= flow capacity at top-of-bank
Q_{MF}=maximum flood on record
$Q_S\uparrow$ =increase in sediment load
$Q_S\downarrow$ =decrease in sediment load
Nkp↑= nickpoint migration
Nrif=Number of Riffles
N/r=Not Reported
P=Wetted Perimeter
PoolL↓ =Pool Length Decreasing
PoolL↑ =Pool Length Increasing
RB=Rock bed
RC=Rock controlled
RifL=Length of Riffle
RI=Recurrence Interval

$S\uparrow$=increase in gradient	$S\downarrow$=decrease in gradient
$\Delta S=0$ (no change in gradient)	Sin=Sinuous
Str=Straight	$W\uparrow$= widening
$W\downarrow$ = constricting	$W{:}d\uparrow$=width to depth ratio increasing
$W{:}d\downarrow$=width to depth ratio decreasing	Win= winnowing
$\Delta W=0$ (no change in channel width)	$\alpha\downarrow$ =decrease in meander amplitude
$\alpha\uparrow$ =increase in meander amplitude	$\Gamma\downarrow$ =straightening (decrease in sinuosity)
$\Gamma\uparrow$=increase in sinuosity	$\xi\uparrow$=increase in meander migration rate
$\lambda\uparrow$=increase in meander wavelength	$\lambda\downarrow$ =increase in meander wavelength
$\phi\uparrow$= increase in bed material size(coarsening)	$\phi\downarrow$=decrease in bed material size (fining)

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2.2.2 Common Impacts Within Channel Segment Upstream of the Mined Reach

The observations reported for the channel segment upstream of the mined reach were the most consistent. Most case studies reported degradation of the bed of the river though the process of headcutting. Headcutting may be associated with an abrupt discontinuity in the bed (a nickpoint) or more simply an over steepening of the longitudinal gradient. The exceptions to this general finding were streams that limited headcutting due to structural or geologic controls. Other exceptions included channels located downstream of major flow control structures such as dams or urbanizing watersheds in which channel incision had already occurred. In the former case incision may be related to the "hungry water syndrom" while in the later case it may have been related to an increase in flow rate and volume.

2.2.3 Common Impacts Within Channel Segment Downstream of the Mined Reach

The incisement of the channel in both the zone of mining and the upstream segment may initiate a process of Valley Formation. This later process results in the formation of a new active channel and floodplain terrace inset within the original floodplain but at a lower elevation. As such Valley Formation results in severe property loss and the influx of large quantities of sediment to the channel system through degradation of the bed and bank collapse. The influx of sediment from the upstream channel segment may result in aggradation within the mined reach (as noted previously) and a concomitant loss of flow conveyance capacity. In many instances the flood hazard reduction benefits obtained through gravel extraction are more than offset by aggradation. Downstream of the extraction zone, sediment is deposited within the channel resulting in aggradation of the river bed and an associated loss in flow conveyance capacity. Aggradation also leads to river widening through bank erosion and plan form adjustment. Table 2.4 summarizes the reported morphological impacts in terms of aggradation or degradation for channels for which mining has been reported to be active or inactive.

Table 2.4. Case Studies Reporting Channel Aggradation or Degradation Relative To Current & Historic Mining Practices

State of Aggregate Extraction	Number of Case Studies Reporting AGGRADATION	Number of Case Studies Reporting DEGRADATION
Inactive	7	0
Active	1	5

It can be seen from Table 2.4 that the channel segments downstream of the mined reach have a tendency to aggrade once extraction within the zone of mining is terminated. As noted in Table 2.4, channels experiencing active gravel extraction tend to degrade in the downstream channel segment. This appears to hold whether the volume of material extracted exceeds supply or whether the coarse material is selectively removed within the mined reach resulting in a finning of bed materials. The reported impact as shown in Table 2.4 is channel degradation leading to incision, widening, and loss of bed armor.

Plan form adjustment tends to be more varied depending upon channel gradient and sediment composition relative to stream competence and capacity. There was insufficient information from the available case studies to draw any conclusions in this regard.

2.3 Discussion of the Morphological Adjustment Process

Gravel extraction for flood hazard reduction or for the commercial value of the aggregate differs little from conventional flood reduction measures when gravel extraction is undertaken at a large scale. Indeed the two management strategies are often linked. At a lessor scale gravel extraction can occur as an independent activity involving the removal of gravel bars through scalping (or skimming) on a periodic basis. On a larger scale gravel extraction can occur as instream pit mining (dredging) or floodplain mining. The skimming of gravel bars is the least intrusive of the mining activities while gravel mining through instream dredging has a greater impact on channel morphology. These activities can result in:

1) widening;
2) deepening;
3) straightening;
4) damage or removal of riparian vegetation;
5) loosening or destruction of sediment structures (imbricate forms);
6) the clearing of Large Woody Debris.

These activities mirror traditional flood mitigation strategies. Consequently, this discussion will deal with the two activities as if they were one and the same.

Pit mining within the floodplain typically becomes an issue when the channel erodes laterally and is captured by the pit resulting in channel avulsion. The morphological impact from these activities is not addressed in this study due to the random nature of the impacts and the lack of documentation.

The following Sub-Sections provide a discussion on the adjustment processes and modes of response as interpreted by the study team based on the literature review.

2.3.1 Channel Response Within the Mined Reach

The active channel in "stable" alluvial systems has been found to be in accord with flows of recurrence intervals of 1:1.5 to 1:2 years (Leopold et al., 1964)[2]. Gravel extraction and flood hazard reduction measures typically enlarged the active channel through lowering of the bed and widening of the banks. This has the effect of:

1) increasing bank height in the active channel;
2) disconnecting the floodplain from the active channel; and
3) increasing the conveyance capacity of the active channel.

The enlarged active channel may contain flows ranging from the 1:5 year to those in excess of the maximum flood on record. Consequently, the original active channel may have the conveyance capacity in excess of the original flood plain channel. The impact on stream power within the enlarged active channel is twofold:

a) during rare flood flow events unit stream power increases; while,
b) during flood flow events equal to or less then the 1:1.5 to 1:2 year flood, unit stream power initially decreases.

The former impact occurs because larger flood flows are contained within the enlarged active channel before they can spill out onto the original floodplain. The later impact occurs because the smaller flood flows are now spread out over a wider channel. Recall that the mid-bankfull to bankfull flow events transport the most sediment and therefore, are responsible for the formation of the active channel. In an in-regime channel system, the dimensions of the active channel represent a balance between the forces exerted on the boundary by these flow events and the resistance of the boundary materials. This balance has been upset with two principle effects:

i) the frequent flood flows (mid-bankfull to bankfull flow) may no longer be able to move the larger particles previously transported by the stream at these flows; and,
ii) the rare flood flows may be able to scour the boundary materials within the enlarged active channel and cause catastrophic failure resulting in channel avulsion.

The above scenario is complicated by other factors associated with instream works including:

1. Removal of Large Woody Debris (LWD) from the channel;
2. Modification or removal of riparian vegetation;
3. Removal of aquatic vegetation;
4. Armoring of the bank materials with cobbles and boulders from the channel bed;
5. The destruction of imbricate sediment structures and the loosening of previously embedded materials; and,

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[2] Leopold, L.B.,Wolman M.G. and Miller, J.P. (1964). "Fluvial Processes in Geomorphology," W.H. Freeman and Co., San Francisco. 522 pp.

6. The alteration of form roughness associated with the straightening of the channel and the loss of pool-riffle definition.

In those instances where the sediment transport potential remains sufficient to transport the sediment load, at mid-bankfull to bankfull flow, an erosional environment may dominate. Bed degradation is the most commonly reported initial response. Where the sediment transport potential is not sufficient to transport the sediment load at these flow rates the stream may drop its sediment load within the previously mined reach. In the former case the channel may continue to incise thereby increasing the flow conveyance capacity of the channel even after cessation of mining operations. If the channel was not already straight or straightened during the "maintenance" program, it will have a tendency to straighten thereby increasing channel slope and unit stream power. The increase in slope may be partially or completely offset, however, by the decrease in bed elevation through incision. Never-the-less, the higher flow capacity of the enlarged active channel will tend to increase stream power for rare flood flow events and the potential for scour of the bed and banks.

Incision of the bed also increases the height of the banks of the enlarged active channel. The banks may also be susceptible to basal scour resulting in an oversteepened state and an increase in the potential for bank failure. The bed armor that may have been placed on the banks is now suspended above the point of secondary maximum boundary shear stress near the bank toe. Failure of the banks, the second most common observation, tends to widen the channel. This has two major consequences:

a) an increase in channel width (W) further increases channel flow conveyance capacity; and,
b) the bank materials may represent a major influx of sediment.

Once again the additional enlargement of the already enlarged active channel affects unit stream power. Unit stream power increases yet more for rare flood flow events but decreases for mid-bankfull to bankfull events with the increase in channel width. If the sediment transport potential is sufficient to transport the sediment load despite the increase in channel width, then degrading conditions may continue until the channel has widened or lost sufficient slope to arrest the downcutting process. If the stream is no longer capable of moving its sediment load then sedimentary processes may dominate.

Within the sedimentary dominated environment the initial response is homogenization of the bed materials (if not already homogenized through instream mining activities) and infilling of the pools (if not previously destroyed). As a result the pool sections tend to become less well defined and shorter, while riffles extend in length. Excessive aggradation may completely bury the pools resulting in a long riffle or run. Consequently, the number of riffles decline while the length of riffles increases.

In the second stage of adjustment, the river's predisposition to concentrate flow results in the development of bar heads (incipient bar forms). This leads to deposition of materials in low bed shear stress regions eventually resulting in an alternating pattern of sediment bars. These bar forms can become massive over several to tens of years after cessation of mining operations if stream capacity and competence is less than the supply of material. Where stream competence and capacity remain relatively high the concentration of flows may also occur but through different processes. The loosened bed materials are susceptible to winnowing. The loss of fines that comprise the matrix within which the coarser materials are found can cause slumping of the coarser particles leaving a depression within which the flows may concentrate. This region of concentrated flow is described as an inset channel. In the sedimentation environment the continued development of the bar forms may also result in the constriction of flow area and the formation of an inset channel. Consequently, both erosional and depositional environments can result in the formation of an inset channel.

The concentration of flows within the inset channel due to the formation of bars has two primary effects:

i) The upper portion of the bars may become vegetated with wood species and stabilized as part of the development of a new flood plain; and,
ii) The toe of the bars may deflect flow into the opposite bank.

The concentration of flows within the enlarged channel and the deflection of flows against the banks opposite the bar forms increases the channels ability to erode its boundary. The channel may respond by re-initiating the downcutting process, tend to widen or both downcut and widen depending upon the absolute resistance of the bed and bank materials and their relative resistance one from the other. If downcutting dominates the channel will repeat the above steps until:

1) the channel slope has been reduced or channel width has increased to the point where unit stream power is insufficient to erode the bed;
2) the channel erodes into a more resistance stratigraphic unit; or,
3) the bed becomes armored.

Following completion of the adjustment phase involving high rates of downcutting, the sedimentary environment is re-established. The formation of bars re-occurs and the channel may re-initiate attack on its banks through basal scour. This process leads to oversteepening and eventual collapse of the destabilized banks. The influx of bank materials and sediments derived from upstream sources may aggravate the lateral instability of the channel. The development of the inset channel through cross-sectional and plan form adjustments will continue until the inset channel is capable of moving its sediment load while maintaining its hydraulic geometry. The new inset channel has a bankfull width that is significantly smaller then that of the former active channel after it was initially enlarged. At this point the inset channel represents the new active channel and the former active channel represents an incipient floodplain channel. The incipient floodplain channel, however, may be too narrow resulting in an entrenched system. Depending upon channel slope and the nature of the bed and bank materials the new active channel may begin to re-meander expanding the incipient floodplain. The result is a new active-floodplain channel system at a lower elevation inset into the original floodplain. This process is referred to as “Valley Formation”.

The above process can be accelerated by catastrophic failure of the system during a rare flood flow event. The increase in bank height associated with channel deepening and the increase in flood flow conveyance capacity make the enlarged channel more susceptible to catastrophic failure. During a rare flood flow event failure of the banks can result in:

a) avulsion (realignment of the channel);
b) degradation of the bed;

c) the formation and rapid upstream migration of nickpoints;
d) large scale bank failure; and,
e) the movement of elevated quantities of sediment into the channel system.

The sediment introduced to the channel or freed from instream storage locations (e.g. sediments trapped behind Large Woody Debris or boulders upstream of the mined reach) during rare flood flow events represent a further complication to the above response scenario. The materials tends to move downstream at different rates depending upon particle size and shape. Smaller materials may be flushed through the system rapidly while coarser material may move through the system during mid-bankfull to bankfull events by traveling from one riffle to the next. Consequently, these materials can take years to be flushed through the channel system. Still larger material may remain as bed armor until moved during a rare flood flow event. Once the supply of these materials has been exhausted and these sediment waves have passed through the subject reach the sediment regime may return to pre-disturbance conditions. If the change in sediment regime is significant relative to stream competence and capacity to move its sediment load, then this alteration in the driving mechanisms must also be addressed.

2.3.2 Channel Response Upstream of the Mined Reach

The process of downcutting within the mined reach creates a discontinuity in the bed profile. In some instances the discontinuity is abrupt and it resembles the riser in a staircase. This form of discontinuity is referred to as a nickpoint (also known as niche point and knickpoint point). Other discontinuities are more gradual. However, both types cause acceleration and de-acceleration of the flow as it passes over the discontinuity. The change in flow hydraulics increases scour potential on the bed. If the bed materials are susceptible to movement under these conditions the discontinuity may migrate headward. As the discontinuity progresses upstream it results in a lowering of the bed and channel incision. This may initiate a process of "valley formation" in which the channel forms a new active and flood plain channel system within the existing valley, but at a lower elevation as noted for the mined reach.

The process of Valley Formation introduces large quantities of sediment into the channel through erosion of the bed and collapse of the banks. The influx of sediment may induce or aggravate aggrading conditions in the downstream reaches. Headcutting of the discontinuity may continue until:

a) the headcut encounters a structural or geologic control point; or,
b) the break of slope created by the discontinuity diminishes to a point where it is no longer morphologically significant.

In many instances the influx of sediment to the mined reach exceeds the amount of material extracted or conveyed downstream. Particulary after cessation of the mining operations. When combined with a loss in channel gradient associated with channel downcutting through mining activities, the flood conveyance capacity within the mined reach may actually decline. The result is an unstable channel form, property loss and loss of flow conveyance capacity within the mined reach. These Impacts are contrary to the intent of the "maintenance" works. Further, the "maintenance" activities negatively impact the reach upstream of the mined segment through accelerated property loss.

2.3.3 Channel Response Downstream of the Mined Reach

The process of valley formation results in the influx of massive quantities of sediment into the channel system. Much of this material is transported downstream, contributing to aggradation within the downstream reaches. Aggrading conditions result in:

1) a net decrease in flow depth;
2) the loss of sediment transport potential;

These effects may lead to a variety of possible morphological impacts including:

a) the formation of massive bar deposits;
b) the siltation of pools:
c) the formation of chutes;
d) more frequent overbank flows;
e) the formation of cutoff channels;
f) the initiation of meander development;
g) accelerated meander propagation;
h) the development of a braided or multiple thread channels systems;
i) the loss of pool-riffle definition;
j) channel widening;
k) channel straightening;
l) increased sediment deposition in the riparian zone;
m) shortening of pools; and,
n) an increase in riffle length.

The exact impacts are a function of stream competence and capacity relative to the alteration in the sediment regime. If the channel is unable to move its sediment load then sedimentary processes dominate channel response as noted above. This is the most commonly documented response mode following cessation of gravel mining operations.

While gravel mining is still active an erosional environment may dominate as noted previously. The primary impacts are:

1) a loss of coarse material through gravel extraction;
2) the reduction in sediment mass being supplied to the downstream reach; and,
3) a net increase in sediment competence and capacity

These impacts may have the following morphological affects:
a) a fining of the bed material;
b) degradation of the bed resulting in channel incision
c) an increase in meander propagation rate;
d) channel widening through basal scour;
e) channel straightening;

f) an increase in channel gradient; and,
g) a decrease in channel sinuosity.

The exact combination of impacts depends upon the sediment characteristics relative to the competence and capacity of the channel system, the type of channel system, and other extraneous factors.

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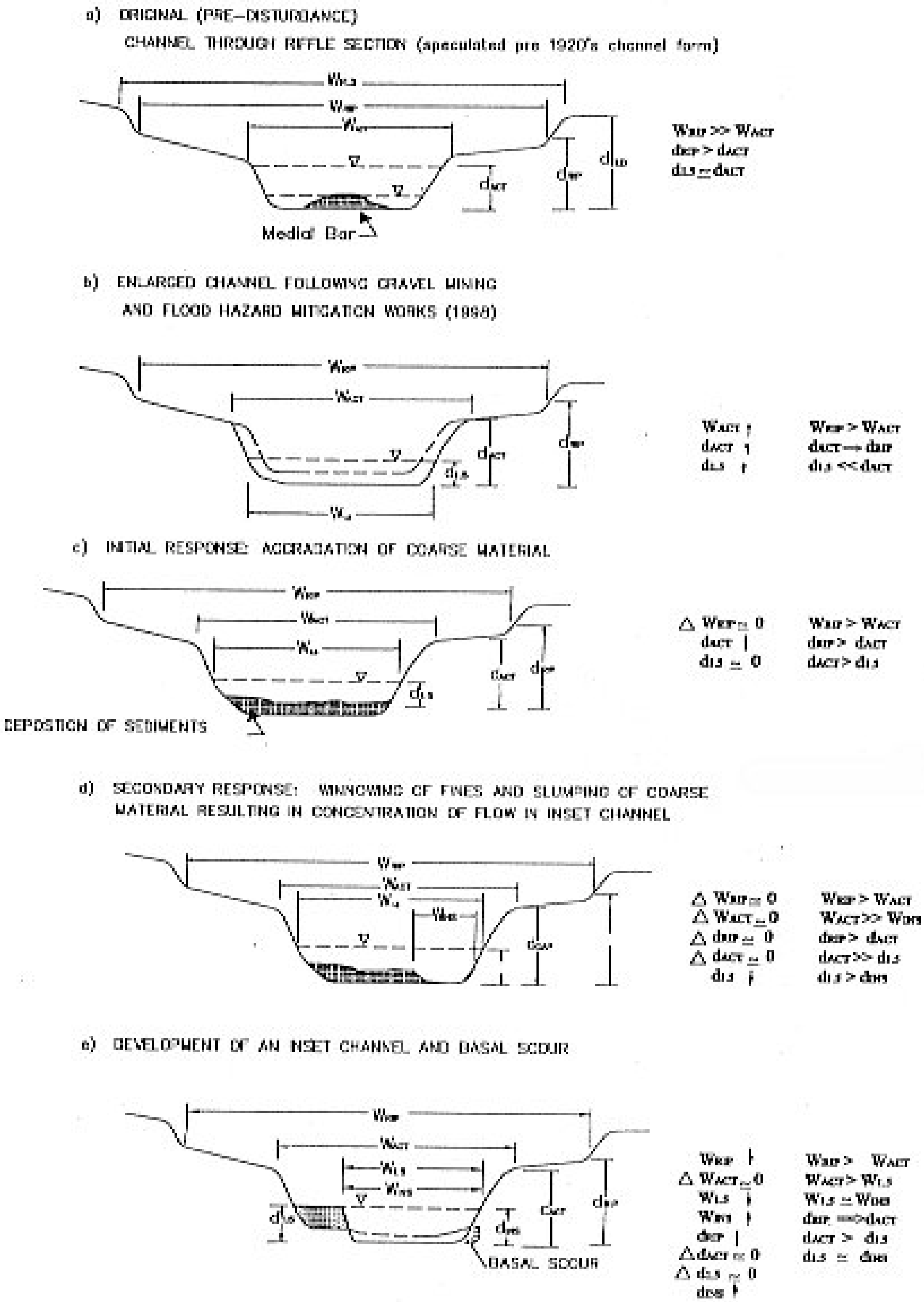
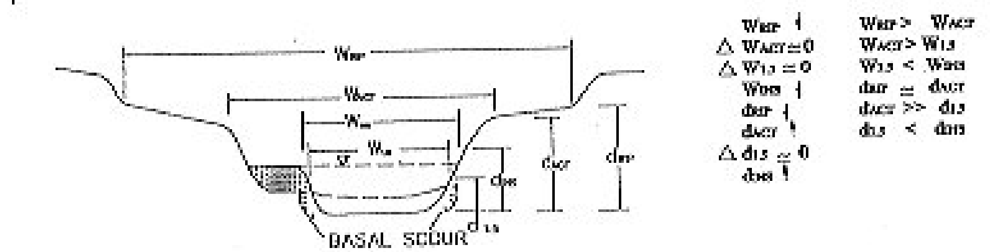
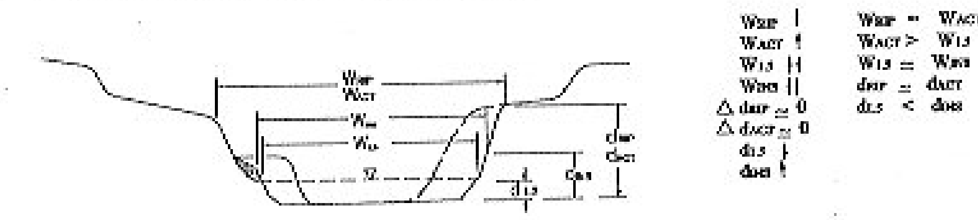


Figure 5.1 Predicted Morphological Response to Gravel Mining and Flood Reduction Activities in the White River near the Town of Granville Upstream of the Confluence with Aldermeadow Brook.

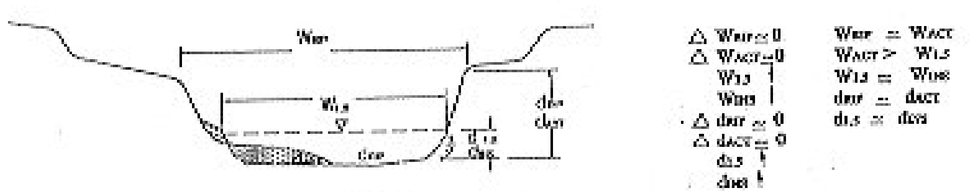
f) NICKPOINT MIGRATION, CHANNEL INCISION & BASAL SCOUR



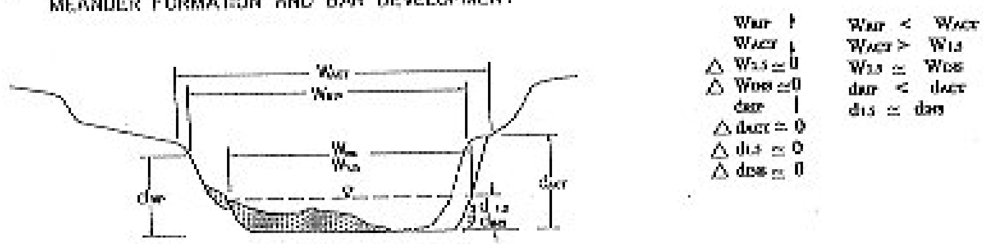
g) CHANNEL ENLARGEMENT THROUGH BASAL SCOUR



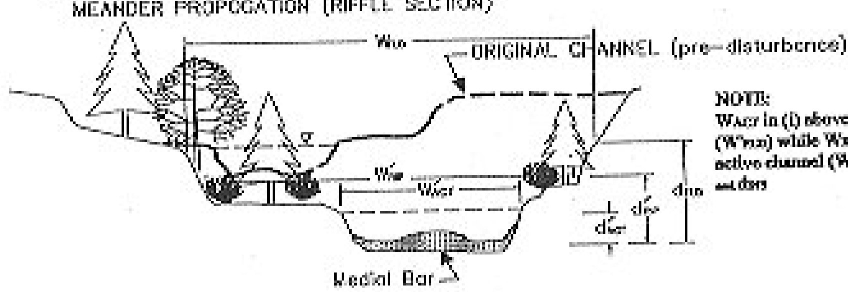
h) AGGRADATION AND BAR FORMATION



i) FLOODPLAIN ENLARGEMENT THROUGH MEANDER FORMATION AND BAR DEVELOPMENT



j) FLOODPLAIN DEVELOPMENT THROUGH MEANDER PROPOGATION (RIFFLE SECTION)



NOTE: W_{ACT} in (i) above becomes new floodplain channel (W'_{FP}) while W_{FP} in (i) above becomes the new active channel (W'_{ACT}). The same applies to d_{ACT} and d_{FP}

Figure 5.1 CONT'D

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