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# An overview of Wood in Rivers

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# Summary

Wood can be used to rehabilitate degraded water bodies (lakes and rivers). However wood has historically been removed from river systems to improve flood protection, inland navigation and drink water quality. These actions reduced and degraded the aquatic habitat of the effected river systems. Rijkswaterstaat is interested in reintroducing wood to rehabilitate the aquatic (and terrestrial) habitat of river systems.

In order to successfully reintroduce wood in river systems it is necessary to identify where the wood comes from? How is it transported? How does it accumulate? And what are the effects on stream ecology and geomorphology? This knowledge can be used to determine if already naturally occurring wood in river systems can be managed to achieve the goal of river rehabilitation. If no or too little wood is present in the river system, an engineered solution can be used. This engineered solution is known as Engineered Log Jam (ELJ). These structures use wood as construction material to rehabilitate rivers. The stability, design and implementation of ELJs in rivers is a complex process.

This report provides an overview on the identification, classification, importance and management of wood in river systems. Secondly the gives an overview of studies done on the stability of wood in rivers, the design (process) of ELJs and the geomorphological impact of ELJs on river systems.

From the studies reviewed in this report it is clear that wood plays an important role in river systems. Wood directly effect river ecology and geomorphology by forming log jams. Proper management of wood is therefore required if one wishes to retain a healthy river system. Where one wishes to (re)introduce wood in a river system using ELJ structures the design process is vital. The first step is to identify the characteristics and properties of the river section. The second step is designing the correct ELJs for the desired goals. The last step is constructing and monitoring the ELJs. Evaluation is important to obtain points of improvement.

# Contents

# 1 | Introduction

The Dutch governmental body *Rijkswaterstaat* is interested in measures to restore ecologically degraded water bodies. A promising solution is the use of wood. Wood in undisturbed river systems is very common. Natural processes such as bank erosion, bank failure and windthrow frequently add wood to river systems as debris. Some of this wood is categorised as Large Woody Debris (LWD). Historically LWD was actively removed from rivers to maintain discharge capacity, improve navigation and to avoid damage and blockage of hydraulic structures (such as piers and bridges). In the United Kingdom the 1732 Laws of Sewers required frequent removal of LWD, weeds and bushes from drinking water sources (Sears, 1732). France enforced the Barnier Law in 1995, after floods in 1993, in which they stressed the importance of managing the riparian zone (the water-land interface of river systems and main input zone of LWD) (Piégay and Gurnell, 1997). Moreover it was assumed that removing LWD benefits fish migration through rivers.

Since mid to late $20^{th}$ century a lot of studies on the effect of LWD on river systems concluded that removal of LWD can have a detrimental impact on river ecology. Moreover LWD impact river geomorphology, shaping river banks, bed and floodplains. The increased awareness of the importance of LWD on river ecology and geomorphology requires a different approach to LWD management. This change in management is most prominent in North America and Australia, where on a governmental level LWD is accepted as a tool to rehabilitate river systems that were previously cleared of LWD, or could benefit from LWD introduction. Therefore most studies are done on North American or Australian river systems, and only few studies focus on European river systems (Piégay and Gurnell, 1997).

Reintroduction of LWD in river systems is a delicate process. Random dumping of LWD can result in unwanted changes in river geomorphology and is a potential risk to hydraulic structures. A solution therefore must be engineered. Engineered Log Jams (ELJs) are engineered structures constructed using LWD as primary building material. ELJs serve as an ecological friendly, cost effective bank stabilisation measures.

This report aims to provide insight in the origin of LWD, its effects and how to use LWD as a rehabilitation measure. The second chapter discusses LWD in natural river systems. How does LWD enter a river system; How to classify river systems in combination with LWD; What are the ecological and geomorphological effects and how to quantify and manage LWD. The third chapter discusses Engineered Log Jams (ELJ). The stability, design and effects of ELJs have been a topic of interest for multiple studies. The third chapter aims to clarify the complexity of ELJ designs and provide guidelines to successful designing.

# 2 | Large Woody Debris

Large woody debris (LWD) is generally defined as logs that are over 10cm in diameter, longer than 1.0m in length and located in the stream region (CDEP). LWD can range from a clean tree bole to whole trees with or without rootward and with or without attached branches, see figure 2.1. The impact of LWD on ecology and geomorphology depends on internal and external processes of the drainage basin area of a stream. Internal processes are the input mechanisms, river size/order and load (volume and jams). External processes are riparian zone (land-water interface) and LWD management.

Figure 2.1: Example of Large Woody Debris, source: fishbio.com

## 2.1 Input mechanisms

In natural river systems, six LWD input mechanisms can be described (Wallerstein and Thorne, 2004). They found that for the North Mississippi river systems the largest two mechanisms are bank failure (36%) and (outer bend) bank erosion (37%). The smaller ones are windthrow (6%), beaver activity (9%), paleodebris (old debris, 7%) and flotation from upstream (5%). Keller and Swanson and Swanson and Lienkaemper categorised the input mechanisms for each river order (section 2.2), table 2.1 (Lassettre and Harris, 2000). For low order river systems LWD input results in stationary single pieces of logs, randomly spaced due to the low stream power to transport LWD. LWD is only transported during debris flows (land- and mudslides, ice loading and avalanches) or by natural decay. Intermediate order river systems have greater stream power and can thus transport some LWD (flotation), but letting it accumulate at certain locations. These accumulations can cause jams in the stream channel. In large order river systems the stream power does not allow LWD to accumulate in the stream channel, but is accumulated at river bars, banks and floodplains.

The jam frequency (per length unit of stream length) decreases as river systems are of a higher order. The piece and jam size also increase with higher order river systems (because stream power increases) (Bisson et al., 1987). The jam size is a counter trend to jam frequency, confirming that as river systems become larger, LWD is transported easier (smaller jam frequency) and accumulates in larger volumes (larger jam sizes).

| | Low order | Intermediate order | High order |
|---|---|---|---|
| Distribution | • Random<br>• Single piece | • Clumped in jams within streams | • Clumped in jams on bars and floodplains |
| Input mechanisms | • Windthrow<br>• Bank erosion<br>• Mass wasting | • Windthrow<br>• Bank erosion<br>• Fluvial transport | • Bank erosion<br>• Fluvial transport |
| Transport mechanisms | • Debris flows<br>• Flood flows | • Flotation | • Flotation |

Table 2.1: Distribution and mechanisms of LWD input and transport, taken from (Lassettre and Harris, 2000).

## 2.2 River Continuum Concept

River systems can vary a lot, from small creeks to the Amazon. But classification of a river system not only depends on the river size, also its behaviour and connection with the riparian zone are important. General classification can be made on river patterns (straight, meandering, braided), flow conditions (perennial, intermittent, interrupted and ephemeral), order (Strahler and Shreve) and Rosgen (Stream) Classification. For the purpose of this research we focus on a classification which includes ecology, the River Continuum Concept.

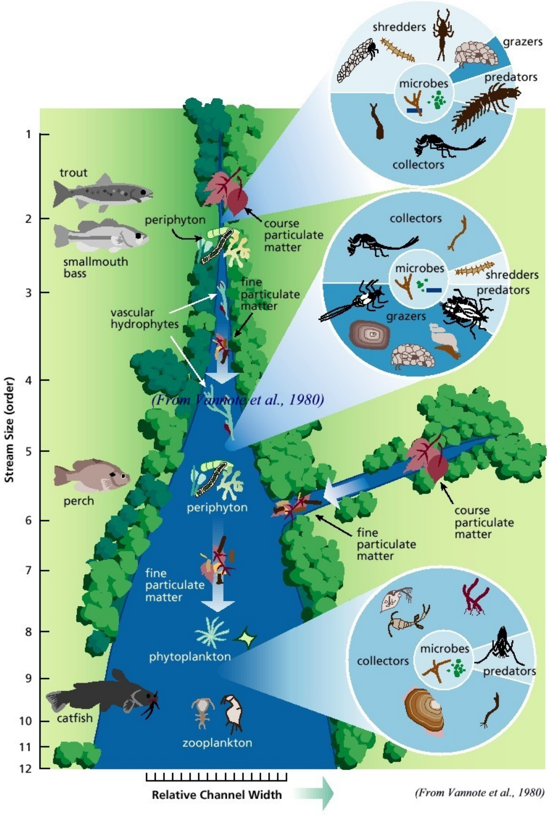


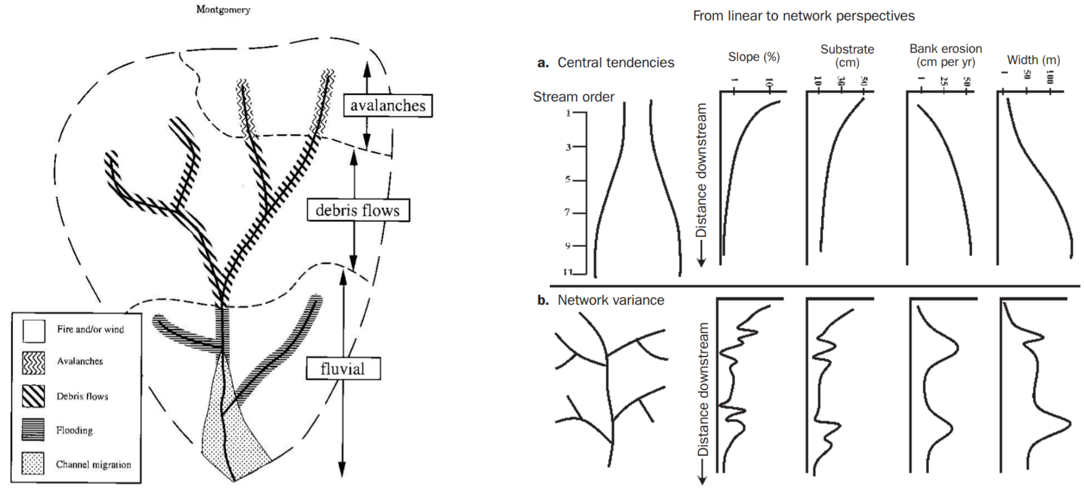
Figure 2.2: River Continuum Concept

In 1980 the River Continuum Concept (RCC, figure 2.2) was conceptualised by to categorise the river systems (Vannote et al., 1980). Multiple studies were done to validate the model, however it is not yet universally accepted (Zaimes and Emanuel, 2006). The model relies on the concept that a watercourse (stream or river channel) is an open ecosystem, continuously in contact with its banks. It combines the physical and ecological characteristics of a watercourse. Physical characteristics can be width/depth ratio, gradient, temperature, turbidity etc.. Ecological characteristics are described by four categories; shredders, collectors, grazers (scrapers) and predators. Shredders feed of coarse particulate organic material (CPOM), like pieces of leaves. Collectors use traps to feed on ultrafine particulate organic matter (UPOM) and fine particulate organic matter (FPOM). Grazers feed on periphyton. Periphyton is discussed in section 2.5.1. These three categories are known as macro-invertebrates (Dutch: macrogewervelden). Predators are the only category that do not feed of plant material.

The RCC categorises rivers as small (headwaters, orders 1-3), medium (mid reaches, orders 4-6) and large (lower reaches, orders 7-12). Headwaters are characterised by a narrow channel and thick vegetation, limiting or restricting penetration of sunlight. Organic material enters the system from external sources, like leaves. Shredders are dominant headwaters as they break down CPOM. Due to the lack of photosynthesis the P/R<1 (Production/Respiration). Mid reaches provide organic material through rocks and LWD on which peripyhton can colonise. Photosynthesis is possible because a wider channel enables sunlight to penetrate and thus the P/R>1. Collectors and grazers dominate these waters because periphyton is present, while shredders are a minority due to lack of CPOM. The share of predators remains unchanged.

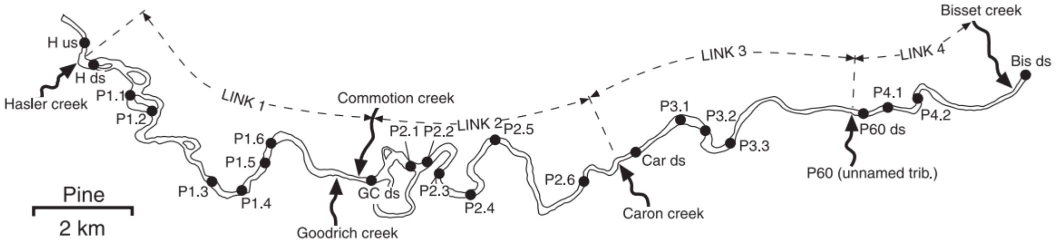
Large reaches decrease again in photosynthesis due to increased turbidity by suspended FPOM, reducing P/R<1. Large reaches are dominated by collectors, with some share in predators. Graphs displaying these processes and more can be viewed in appendix A.

The original RCC does not account for tributary (Dutch: zijrivier) effects. Three adaptations of the RCC are made to account for tributary effects. These are the Process Domain Concept (PDC), Link Discontinuity Concept (LDC) and Network Dynamics Hypothesis (NDH). PDC divides a river system into domains based on similarities in ecological and geomorphological characteristics (Montgomery, 1999), figure 2.3a. LDC is the idea that tributaries divide a system into links (figure 2.3c). At the transition of one link to the other discontinuities (steps) occur in the physical and ecological characteristics of the system (Rice et al., 2001), see appendix B for tributary effects. NDH is "a combination of PDC and LDC" and considers the entire system (network), (Benda et al., 2004). It acknowledges that domains can be determined with similar characteristics and also account for the influence of tributaries. NDH follows the logic of the RCC, but accounts for network variance due to the effects of domains and tributaries.



(a) Process Domain Concept

(b) Network Dynamics Hypothesis



(c) Link Discontinuity Concept

Figure 2.3: RCC adaptations to account for tributary effects

## 2.3 Urban Channel Evolution Model

### 2.3.1 Classic Channel Evolution Model

The RCC is a classification method for river systems. Another type of classification is the Channel Evolution Model (CEM). The model is used for single-threaded, unstable sand-bed river systems. Multi threaded (braided) systems closely follow single-threaded systems for increased flow, lowered bed level, channelisation and sediment transport (Hawley et al., 2012). A CEM describes the evolution of a river channel in several stages. Each stage is downstream of the previous stage. Generally a CEM can be used as a predictive and diagnostic tool. This can be done because of the cause-consequence relation of CEMs. The current channel characteristics (stage) can be interpreted as a cause when predicting channel evolution, and as a consequence when diagnosing channel changes. Different CEMs exist, each (slightly) different from the other. The focus here is on the incised CEM by Schumm et al. (1984), developed for the North Mississippi river (figure 2.4). Five stages are defined, explained below:

Stage 1 Cross section is U-shaped with floodplains. Little to no sedimentation (dynamic equilibrium).

Stage 2 Dominated by bed degradation. Sediment capacity exceeds supply because the reach is oversteepened. No instability of banks yet, because $h < h_c$.

Stage 3 As the bed continuous degrading, the critical bank height will be exceeded ($h > h_c$). Bank failure drastically increases channel width. Bank failure can add to the sediment supply and reduced bed gradient reduces sediment capacity, resulting in the initiation of sedimentation of the channel bed. Floodplains are now terraces.

Stage 4 Bank failure and channel widening may continue, but at a much lower rate ($h \leq h_c$). Further increased sediment supply and decreased capacity allow for significant bed aggregation.

Stage 5 A new dynamic equilibrium is reached ($h < h_c$). Berms (floodplains), first present in stage 4, are now colonised by riparian vegetation. Local instabilities of banks can still occur due to meandering of the channel, obstructions and constructions.

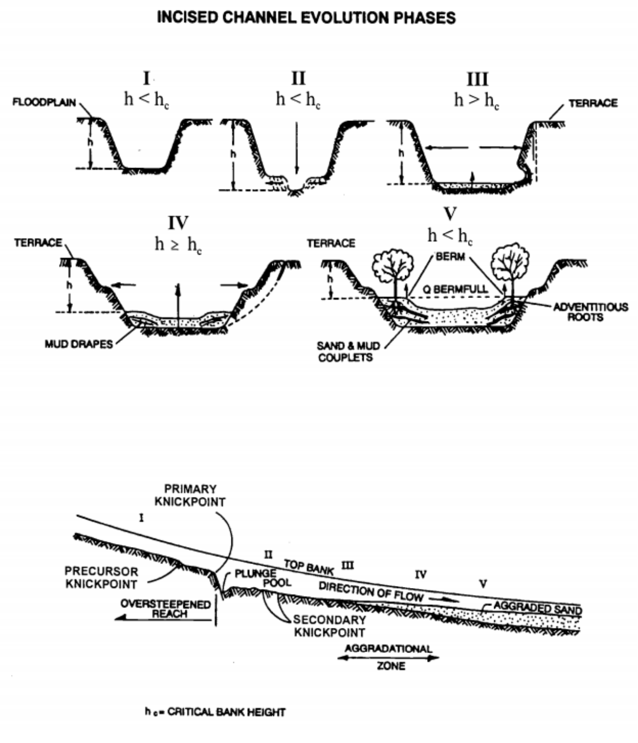


Figure 2.4: Channel Evolution Model (Schumm et al., 1984)

Wallerstein and Thorne (Wallerstein and Thorne (2004)) did a study on 23 reaches of the North Mississippi river system (sand-bed system), see figure 2.9. Of the 23 reaches, 17 were found to have debris jams (jams are discussed in section 2.4). The riparian zone of all six reaches where no jams were found were all cleared of natural vegetation for agricultural purposes. The basins with jams were also located in agricultural zones but the riparian zone was mainly left untouched and only fenced off. The number of jams per 100m sub-reach and the total volume of LWD in the jams per 100m sub-reach were related to the CEM stages. The results are shown in figure 2.5. The results are in line with the expectations. CEM stage 1 has little LWD input because the banks are stable. LWD input is increased in CEM stages 2 and 3 because of local bank failure and channel widening. Improved bank stability in CEM stage 4 reduces LWD input. Meandering in stage 4 can still cause LWD input and retention. In CEM stage 5 banks are stabilised and riparian vegetation is colonised on the floodplains. LWD input and retention can be reduced to values smaller than for stage 1, however this is not observed in their study. The standard deviation for stages 2 and 4 are relatively large due to the low number of reaches of these stages. More data would increase accuracy (Wallerstein and Thorne, 2004).

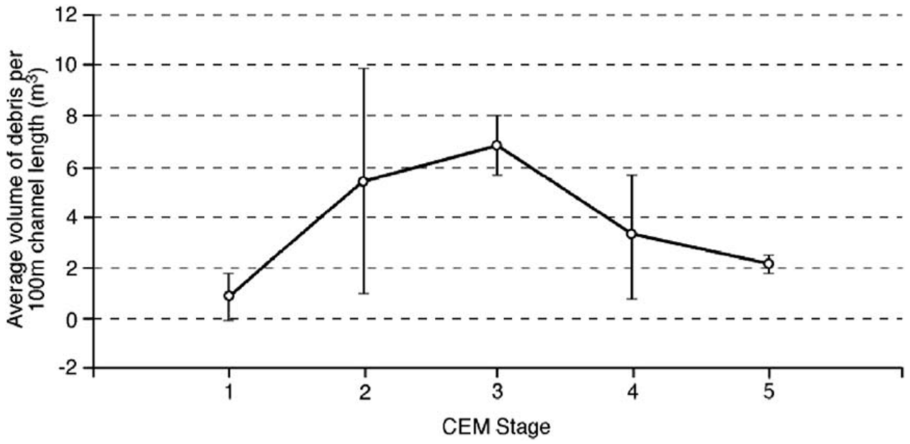


Figure 2.5: Average and 1 standard deviation for each CEM stage (Wallerstein and Thorne, 2004).

### 2.3.2 Urban Channel Evolution Model

Channel Evolution Models best describe the evolution of single-threaded incised channels, however urban disturbances do not always have a similar effect on channel evolution. An Urban CEM (UCEM) includes the effect of urban disturbances on channel evolution. Such a model is developed by Booth and Fischenich (2015).

The first aspect to consider is that urban channels are usually constrained in horizontal and/or vertical direction (i.e. non-alluvial channels). Channel deepening and widening, present in the classic CEM, are therefore unable to (fully) develop in these channels. Protected embankments and dikes prevent widening of the channel. Immobile beds (e.g. concrete slabs, rock bed protections) effect sediment transport. Moreover weirs, locks and dams directly effect water levels and sediment transport. Clearing of in-channel LWD and riparian vegetation are also non-alluvial disturbances (Booth and Fischenich, 2015). A table with ten urban disturbances is presented in appendix C. This table focuses on the three main urban disturbances; erosive discharges, reduced sediment transport and horizontal and vertical constrains.

Just like CEMs, the UCEM can also be used as a predictive or diagnostic tool. The predictive version is graphically shown in figure 2.6. The diagnostic version is presented as a table, see appendix C. An increase of discharge or decrease of sediment transport for single-thread alluvial channels can result in expansion, or incision and widening (classic CEM), depending on the magnitude of the disturbance. For braided alluvial channels, all three disturbances can potentially transform the channel into a single-threaded channel due to incision. Also if the increased discharge changes the channel discharge from intermittent to perennial, vegetation can grow and transform the channel to single-threaded. For all channels bed coarsening is mentioned. This is a consequence of increased discharges that more easily transport fine sediments and reduced sediment transports that transport less fine sediments. Increased sediment transport leads to bed fining, as can be seen for single-threaded non-alluvial channels.

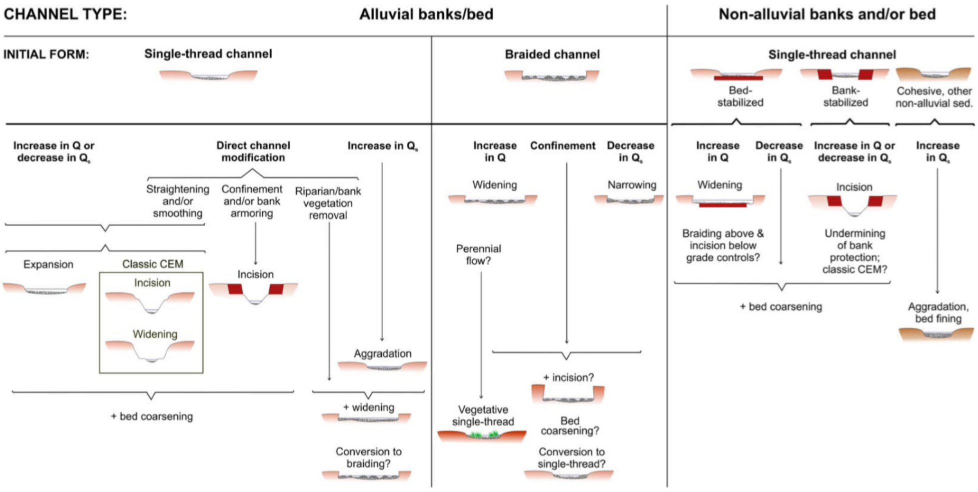


Figure 2.6: The UCEM as a predictive tool

## 2.4 Debris jam classification

Several methods to categorising LWD jams have been developed. Two methods are discussed here. The first method is presented by Gregory et al. (1985). They categorised LWD jams (debris jams) for small to medium sized rivers. LWD jams (dams) were classified in three categories. Active dams span the entire width of a channel, creating a significant step in the water level (even at low discharge). Complete dams are active dams that do not create a step at low discharge. Partial dams do not span the entire width of the channel and are usually oblique to the flow direction. Wallerstein and Thorne (2004) defined the Debris Jam Classification Scheme (DJCS), a modification of the pool morphology classification scheme by George Robison and Beschta (1990), see figure 2.7. The ratio of log length (l) and channel width (B) defined the boundaries of each jam type. From figure 2.7 one could argue that underflow jams are complete dams, dam jams are active dams and deflector and bar head jams are partial dams. Unfortunately this it not confirmed. Each DJCS jam type corresponds with certain morphological responses:

- Underflow type jams barely interfere with the flow and therefore do not have a high scour and sedimentation potential.
- Dam type jams cause large volumes of sediment to be stored in backwater areas, but also cause plunge pool scour downstream of the dam.
- Deflector jams cause sediment to be trapped on their lee side, but also cause flow acceleration on one or both banks resulting in scour and bank erosion/failure.
- Flow Parallel/Bar Head jams blocks flow to a lesser extent. Sedimentation and scour is reduced compared to deflector jams.

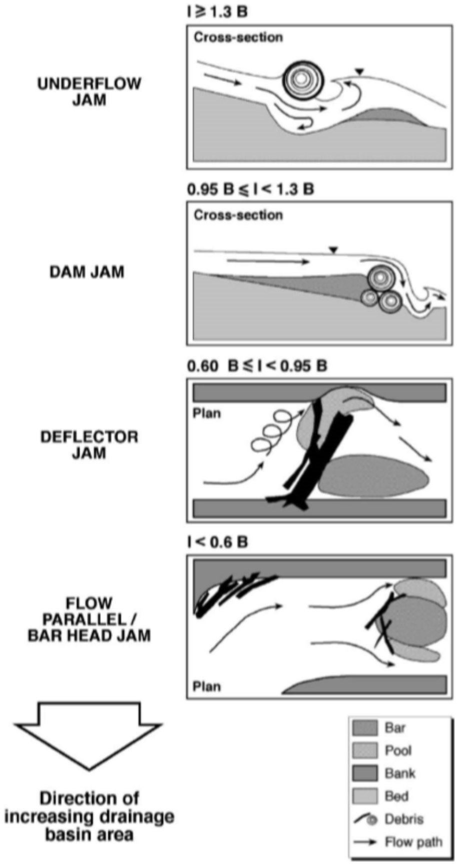
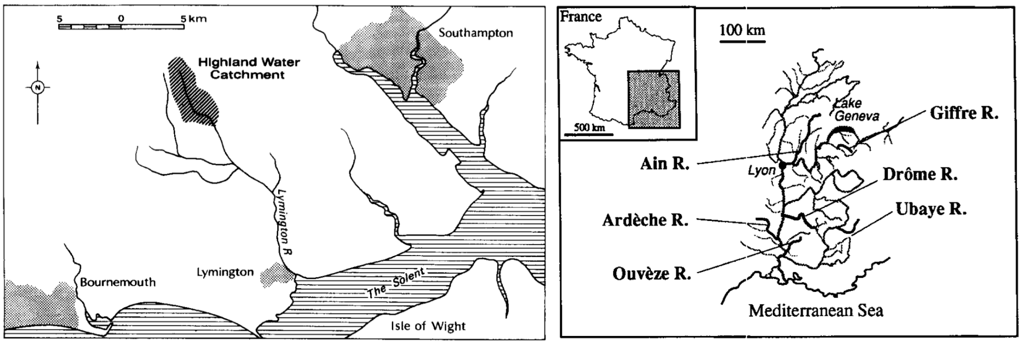


Figure 2.7: Debris Jam Classification Scheme

### 2.4.1 Classification for small and medium sized rivers

Piégay and Gurnell (1997) researched the impact of LWD on European rivers. Two areas were chosen, the Highland Water Catchment and piedmont (mountain base) rivers in South East France, see figure 2.8. The Highland Water Catchment region consists of small-medium river systems. The large piedmont river systems consist of braided systems (Drôme, Giffre, Ubaye and Ouvèze) and wandering (meandering) systems (Ain, Ardrèche).



(a) Small-medium rivers (b) Large piedmont rivers

Figure 2.8: Locations of the European rivers studied by Piégay and Gurnell

The data on LWD jams is presented in table 2.2. Noticeable is the reduction in complete jams and increase of partial jams for greater order rivers. This concluded that LWD in small and medium-sized rivers directly impact the aquatic surface because LWD can span the entire width of small rivers creating transverse log jams. For medium-sized rivers, debris jams are less likely to occur since the hydraulic power is greater and LWD is less likely to span the entire width of the channel. This makes the transport of LWD easier. For large rivers LWD is easily transported and jams are a rare occurrence.

| River stretch | RCC Order | Number (%) of different jam types | | | |
|---|---|---|---|---|---|
| | | Partial | Complete | Active | Total |
| Main Highland Water (1984) | 3-4 | 109 (64%) | 41 (24%) | 21 (12%) | 171 |
| Upper Highland Water (1991) | 1-2 | 7 (19%) | 17 (46%) | 13 (35%) | 37 |
| Bagshot Gutter (1991) | 1-2 | 0 (0%) | 35 (85%) | 6 (15%) | 41 |

Table 2.2: Frequency of LWD dams in small-medium rivers of the Highland Water Catchment area. Main Highland Water is shown for 1984 because in 1990 this section was actively cleared of dams.

The impact of LWD in large systems is very variable. Braided systems have a lower retention capacity than wandering systems due to lack of sinuosity (lack of meandering) and second channels that are not narrow enough to capture transported LWD. Secondly in braided systems the supply of LWD is limited. Frequent flooding prevents development of large riparian vegetation in the main channel.

LWD in wandering systems are generally deposited at the edges of the main channel and on the floodplains. LWD located on the floodplains cause local scour during floods, creating single channels. These channels can contribute to channel cut-off and reshape the floodplains. LWD deposited in the outer bends can significantly impact the erosion rate of the river banks (Piégay and Gurnell, 1997).

### 2.4.2 Debris Jam Classification Scheme

The study by Wallerstein and Thorne (2004) previously discussed applied the DJCS to the debris jams in the 17 reaches. Ordering the reaches in ascending drainage basin area, the cumulative percentage frequency for each jam type for all 17 drainage basins can be extracted, shown in 2.10. From this graph a trend can be observed. The number of underflow and dam type jams decrease with increasing basin area, while deflector and bar head type jams increase with basin area. This trend is similar to the trend found by Piégay and Gurnell (1997) for active/complete/partial dams. However the trend found by Wallerstein and Thorne (2004) is weak due to the fact that the number of large basins studied is small.

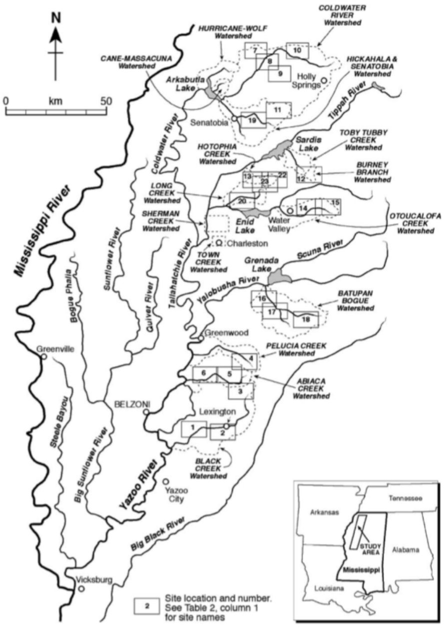


Figure 2.9: Study area of the North Mississippi river system.

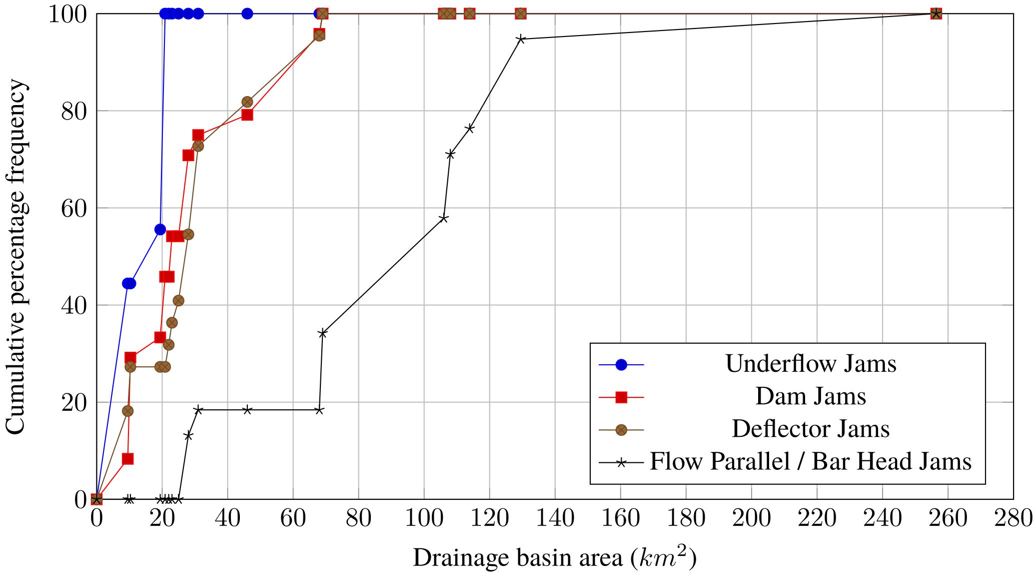


Figure 2.10: Cumulative jam frequency as a function of drainage basin area.

## 2.5 Impact on ecology and geomorphology

### 2.5.1 Stream ecology

LWD has a significant impact on the ecology of streams (CDEP; Hilderbrand et al., 1997). Firstly LWD blocking a stream section or span the full channel width are suitable habitats for fish. Local flow velocities can greatly be reduced, providing shelter. Pools that are formed upstream of the LWD can act as a buffer of water in periods of low discharge. LWD can also trap sediments and organic material such as leaves that provide a food source. Secondly periphyton can attach and grow on LWD. The United States Environmental Protection Agency (USEPA) defines periphyton as *"A mixture of microscopic plants and animals that firmly attach to solid surfaces such as rocks, logs, and pilings"*. Periphyton is a good indicator for water quality. The USEPA states the following advantages of using periphyton as a water quality indicator (Barbour et al., 1999):

- Algae generally have rapid reproduction rates and very short life cycles, making them valuable indicators of short-term impacts.
- As primary producers, algae are most directly affected by physical and chemical factors.
- Sampling is easy, inexpensive, requires few people, and creates minimal impact to the direct environment.
- Relatively standard methods exist for evaluation.
- Sensitive to some pollutants which may not visibly affect other aquatic life, or may only affect other organisms at higher concentrations (i.e., herbicides).

Besides periphyton, another good indicator is benthic ("bottom-dwelling") macro-invertebrates (Dutch: bodem macro-gewervelden), typically categorised as shredders, collectors and grazers. These are small aquatic lifeforms, visible with the eye, and the main food source for fish. These two indicators are short term. Fish on the other hand is a long term indicator of water quality. The variety and diversity of fish communities indicate the level of integration of fish in the local ecosystem (larger and higher is better). Moreover LWD provide habitat for birds that feed of small aquatic life. In brief LWD create micro-ecosystems, as depicted in figure 2.11.

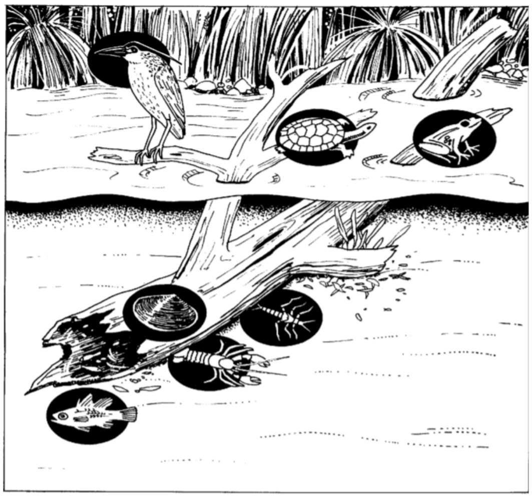


Figure 2.11: Micro-ecosystem of fauna as a result of LWD. At the base of the micro-ecosystem are periphyton and macro-invertebrates, illustration by Dickinson Art (Trayler, 2000).

### 2.5.2 Stream geomorphology

Stream geomorphology is the combination of topography of a stream system (channel, banks and floodplains) and bathymetry (stream bed). LWD (re)shapes stream geomorphology by blockage and redirection of flow. Blockage of a flow creates backwater pools and sedimentation. Redirection of flow can cause erosion of the bed and/or banks.

The ecological, hydraulic and morphological impacts of LWD (qualitative and comparative) according to river size and pattern of the European rivers researched by Piégay and Gurnell (1997) is summarised in table 2.3. The table shows that LWD has the most significant impact on geomorphology in wandering systems. The magnitude of the impact of LWD on river systems is very variable because it depends on three main factors, channel size, bed morphology and the characteristics of the bank and riparian zone. No two systems have similar characteristics and thus neither is the impact of LWD. Nonetheless the general effects of LWD are relatively consistent.

| | Small-medium rivers | Large piedmont rivers | |
|---|---|---|---|
| | | Braided | Wandering |
| Creation of terrestrial habitat | - | + | ++ |
| Creation of aquatic habitat | ++ | + | + |
| Increase in inundation frequency | + | - | = |
| Diversification of the flood plain mosaic | = | - | ++ |
| Increase in bank erosion | - - | - | ++ |
| Increase in sedimentation | + | ++ | + |

Table 2.3: Ecological, hydraulic and morphological impacts of LWD ++ very significant; + significant; = moderate; - weak; - - very weak (Piégay and Gurnell, 1997).

Based on their results, Wallerstein and Thorne (2004) presented a table (table 2.4) for LWD impact in unstable, sand-bed rivers. They concluded that Underflow and Dam jams act as sediment storage (flow blockage and energy dissipation) and Deflector and flow jams cause scour of the bed and banks (flow deflection).

| Impact | Jam type | | | |
|---|---|---|---|---|
| | Underflow | Jam | Deflector | Flow parallel / Bar head |
| Debris blockage | low | high | high | low |
| Increased bank erosion | low | moderate | high | low |
| Increased bed erosion | high | moderate | low | low |
| Increased sediment storage | low | high | high | moderate |
| Increased bed topography variability | high | high | high | moderate |
| Aid to local channel stability | high | high | high | high |
| Increase in frequency and duration of overbank flooding | moderate | high | moderate | low |
| Increased fish habitat diversity | high | high | high | high |
| Blockage to fish migration | low | high | moderate | low |

Table 2.4: LWD impact in unstable sand-bed rivers (Wallerstein and Thorne, 2004)

## 2.6 Large Woody Debris Survey and Index

Davis et al. (2001) developed a manual for biologists and wilderness managers about the monitoring of wilderness stream ecology. This manual was developed because knowledge about wilderness stream ecology was little to none, and impact assessment by nature and humans was not yet registered. In their manual they stressed the importance of LWD in stream ecology and geomorphology and described what is known the Large Woody Debris Index (LWDI). This index quantifies the relative importance of LWD on wilderness stream ecology and geomorphology. Another method, developed by Schuett-Hames et al. (1999), put more focus on individual logs of LWD. Their method is referred to as Large Woody Debris Survey (LWDS). The difference in focus is most apparent when looking at the criteria, see table 2.5. LWDS quantifies each log/jam, giving them a number and allocating dimensional properties (log or rootward, tree species, piece decay, number of logs per jam) and also addresses pool forming function (ecology) and sediment storage (geomorphology). LWDI is more generic, specifying only spatial relations (length/bankfull width, jam length and height in %) and characteristics (structure and type) of LWD in the stream channel. These criteria point towards a more geomorphology oriented assessment. The definitions of each criteria are given in appendix D, as well as the quantification table for LWDI. A detailed manual for application of the LWDI can be found in the report by Harman et al. (2017).

| Criteria | LWDS | LWDI |
|---|---|---|
| **Large Woody Debris** | | |
| Piece number | ✓ | |
| Downstream reference point association | ✓ | |
| Log/Rootward identification | ✓ | |
| Length/bankfull width | | ✓ |
| Diameter | ✓ | ✓ |
| Zone location | ✓ | ✓ |
| Orientation | ✓ | ✓ |
| Type | | ✓ |
| Structure | | ✓ |
| Stability | ✓ | ✓ |
| Tree species | ✓ | |
| Pool forming function | ✓ | |
| Piece decay | ✓ | |
| Sediment storage | ✓ | |
| **Debris Jam/Dam** | | |
| Jam number | ✓ | |
| Jam reference point association | ✓ | |
| Zone location | ✓ | ✓ |
| Length (% of bankfull width) | | ✓ |
| Height (% of bankfull height) | | ✓ |
| Tally of visible pieces by category | ✓ | |
| Structure | | ✓ |
| Stability | | ✓ |
| Pool forming function | ✓ | |

Table 2.5: Large Woody Debris Quantification Criteria

## 2.7 Large Woody Debris management

From previous sections it is now clear that the impact of LWD on stream ecology and geomorphology is dependent on many aspects. It is therefor wise to review the impact of LWD individually for each stream of interest. Management of LWD is therefore not straight forward. Nonetheless five general management methods can be described (JFNew, 2007):

- No action
- Clean and Open
- Removal
- Re-positioning, placement and anchoring
- Preemptive cutting and anchoring

No action can be taken when the LWD does not directly obstruct the channel (<10% of cross-sectional area) and is unlikely to move. The Clean and Open method is the simplest method of LWD management. It only requires some changes to the structure, like reducing channel blockage by changing the orientation while retaining the anchor point. It is necessary to check if additional anchoring is required. Removal of part of the LWD can be done to reduce blockage while the remaining LWD keeps the initial function. Close monitoring is required to ensure that LWD function is not lost. The removed LWD can be re-positioned and if required anchored to, for example, stabilise banks. LWD that is placed in a stream is can consist of singular logs or structures. In the case of a structure these jams are usually referred to as Engineered Log Jams (chapter 3). Preemptive cutting and anchoring of LWD can be done to prevent LWD from entering the channel and potentially blocking the stream, creating a debris jam and significantly impacting stream geomorphology.

# 3 | Engineered Log Jam

Historically removal of LWD from streams was assumed to have a positive impact on ecology and geomorphology, but research shows the opposite is true (chapter 2). LWD plays a very important role in the ecology and geomorphology of streams. Many (regional) governments, especially in North America and Australia (NSW DPI, 2018), acknowledge this. Projects to reintroduce LWD in streams have been started, completed and evaluated. This reintroduction of LWD in river streams is sometimes done by constructing what is called an Engineered Log Jam (ELJ). ELJs resemble natural accumulations of LWD that form jams or dams in streams. Their primary purpose is to act as a soft construction alternative to channel stabilisation (especially bank stabilisation). Secondary effects are increased water quality, improved ecology and if done correctly very cost effective. Many projects were successful in stabilising channel banks, creating aquatic and riparian habitat as well as debris retention (Abbe et al., 1997; Drury et al., 1999; Larson et al., 2001; McHenry et al., 2007; Daley and Brooks, 2013). Debris retention is a secondary effect of ELJs where driftwood is retained by the structure, preventing potential risks to hydraulic structures such as bridge piers.

This chapter first discusses research on the stability of LWD in streams in section 3.1. From this research a general design of an ELJ can be defined, section 3.2. The hydraulic impact of ELJs used as bank protection is reviewed in section 3.3.

## 3.1 Stability of Large Woody Debris

In order to correctly design an Engineered Log Jam, and to have it function similarly to LWD jams it is necessary to know what makes LWD jams stable. The first parameter that has a big effect on stability is the log length/channel width ratio. Lienkaemper and Swanson (1987) found an inverse relation of log length to channel width (a similar trend to debris jams, section 2.4). However this does not mean that shorter logs are always unstable. LWD jams consist of various sizes of logs. Logs that are larger than the channel width are likely to also remain stable under high flow and can retain smaller logs and other small debris (Hilderbrand et al., 1998). Studies by Abbe et al. (1993) and Lienkaemper and Swanson (1987) show that LWD tends to be most stable when the log length is greater than half the bankfull width in large rivers or greater than one bankfull width for small rivers. Secondly LWD tends to be more stable when greater than half their length is outside of the channel area (not exposed to flow).

Braudrick and Grant (2000) tested a simple model for single log entrainment with and without rootward (appendix E). They considered the gravitational, friction and drag forces and neglected lift forces. The lift force was assumed negligible because in their model, logs were not fully submerged. They also only considered movement of the pieces by sliding, not pivoting (when oblique or normal to flow direction). The bed consisted of immobile coarse grains. Their results are shown in figure 3.1. As is expected, pieces oriented parallel are more stable than pieces oblique or normal oriented. The drag coefficients had to be estimated and were considered to be inaccurate. However increasing or decreasing the coefficients by 50% changes the predicted value only slightly larger than symbol size (Braudrick and Grant, 2000).

It was observed that the model underestimated the stability of pieces oriented parallel (0°) in all cases. Braudrick and Grant (2000) stated that this was likely due to irregular roughness elements of the bed. The irregularity can cause an interlocking effect of the downstream piece end with a bed grain, preventing movement. For logs oriented oblique and normal the model was more accurate. Smaller diameters moved at values larger than predicted, while the larger diameters moved at values smaller than predicted.

Pivoting was not considered in the model. Nonetheless it appeared to be an important initiation of motion for all pieces oriented oblique and normal. Pieces without rootwards pivot and roll towards 0° while moving downstream. Similarly for pieces with rootwards, however after pivoting a new stable position was acquired just downstream of the initial location. At this position the downstream end of the piece (non-rootward end) would at some point float. The piece is then dragged over the bed. The pivoting effect for pieces with rootwards is the likely cause of them moving before their predicted values.

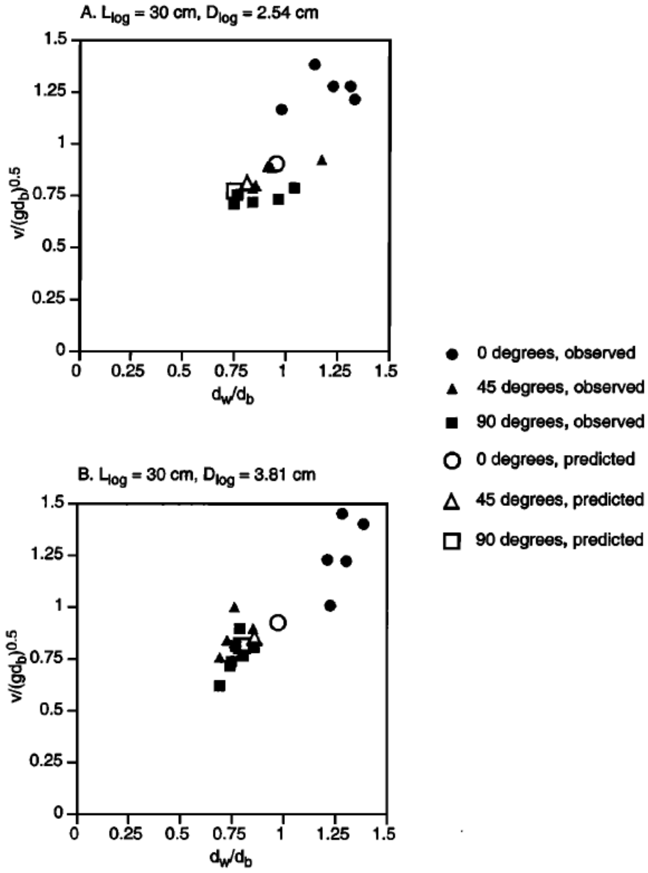


Figure 3.1: Experimental results Braudrick. More graphs in appendix figure E.3.

The study showed that the entrainment of logs is more complex than a simple model. The variability in log properties (diameter, length, rootward, density, shape) and orientation (parallel, oblique, normal), as well as secondary effects such as bed material and pivoting create a complex system. The importance of bed material is also stressed in a study by Member) et al. (2013) due to scour formation increasing local water depths. Braudrick and Grant (2000) advised that a model for entrainment should include mobile bed processes. However for pieces oblique and normal to the flow, without rootward, the simple model predicted movement within 20% of the observed values. Moreover in medium and large size rivers, logs tend to stabilise at river banks due to the presence of boulders and riparian vegetation. Therefore diameter is dominant over length for stability, as the length is (much) smaller than the bankfull width of the river. In these scenarios the presence of a rootward also appear to be dominant over length.

A more practical experiment was conducted by D'Aoust and Millar (2000). Ballasted LWD structures were placed in streams to test a predefined safety factor (appendix F). Three types of structures were tested, Single-LWD Structure (SLS, i.e. deflector log), Single-LWD with intact rootward structure (SLRWS, i.e. bar head) and multiple-LWD structure (MLS, i.e. deflector jam), see figure 3.2. The structures were evaluated after a period of one year.

The results, shown in appendix F, show that the approach used by the authors was successful in predicting the stability of SLS and SLRWS, where differences could be accounted for underestimations of ballasting forces. For MLS the approach was less successful where about 25% of the structures did not agree with their predictions. Likely causes for this was incorrect construction of the MLS (e.g. loose cabling), accumulation of debris upstream of the structure, increasing lateral forcing and local bank and bed scour formation. The safety factor for buoyancy for MLS was deemed too simple.

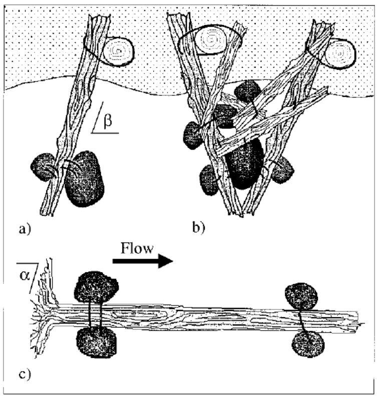


Figure 3.2: Illustration of LWD structures: (a) SLS; (b) MLS; (c) SLRWS

Hilderbrand et al. (1998) found that different type of jams resulted in different bed elevation change patterns, see figure 3.3a. Similar results were found by Cherry and Beschta (1989), figure 3.3b. Moreover Cherry and Beschta (1989) concluded that LWD is oriented primarily downstream (between 0○ and 80°, 41%) and perpendicular (between 80° and 120○, 39%) to the flow direction, while only 20% was oriented upstream (between 120○ and 180○). Degrees are measured counterclockwise, South to North. Their tests showed that the deepest scour occurred for logs perpendicular to the flow direction. The location of maximum scour depth was at the middle of the dowel when placed flat on the bed, and slightly more to the right edge of the log when elevated.

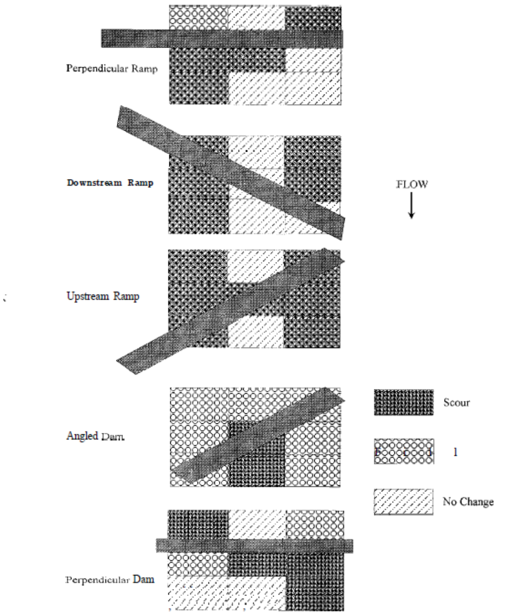


FIGURE 2.-Average changes in channel elevation for different log orientations. Dams were flat on the streambed; ramps had one end propped on the stream bank.

(a) Average changes in channel elevation for different log orientations. Dams were flat on the stream bed; ramps had one end propped on the stream bank (Hilderbrand et al., 1998).

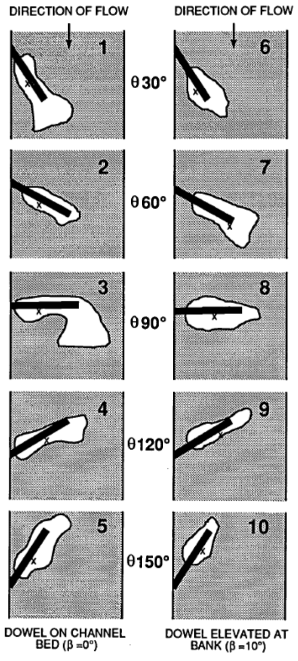


Figure 2. Representative Scour Patterns Associated with the Ten Test Orientations. "X" Indicates the Location of Maximum Scour at the End of a Run.

(b) Representative scour patterns. "X" indicate the location of maximum scour. Beta is the vertical angle of the dowel (Cherry and Beschta, 1989).

Manners et al. (2007) conducted a study on the structure and hydraulics of natural LWD jams. They measured the surrounding velocity, shear stress and drag force. For a single jam they measured these parameters for four stages: wrapped, natural, partial and key member. These stages resemble the volume of material from high to low and porosity from low to high (figures, see appendix G). Figure 3.3 shows that for a key member, the excess shear stress (indicating areas of erosion) is maximum at a similar location downstream as was found by Cherry and Beschta (1989) for dowels flat on the bed at 30° (figure 3.3b).

These studies show that determining the stability of LWD (structures) is not straightforward and simple models are only moderately accurate. Nonetheless these simple models give a first estimation of the stability of potential ELJ designs. For example these models can be used to determine the stability of the first layer of logs placed on the bed/bank of a river. Secondary layers can then be used to help stabilise the structure further and adding functionality according to its purpose (e.g. bed/bank protection and flow deflection). A large effect that is difficult to model is the effect of bed material on the stability. The studies by Hilderbrand et al. (1998); Cherry and Beschta (1989); Manners et al. (2007) show that erosion patterns occur up- and downstream. Erosion can potentially cause local failure, leading to global failure of the structure and its effect should therefore not be underestimated.

## 3.2 The design of an Engineered Log Jam

The design of an ELJ is in essence the stacking of logs to create a stable structure. Three aspects are key: use of buoyant material, use of gradually decaying material and a dual purpose of channel stabilisation and habitat rehabilitation (Shields et al., 2004). A typical plan of an ELJ consists of key, stacked and racked members, see figure 3.4. The key members ensure stability by bank anchoring (typically logs with a rootward). Stacked members are used to create a connecting structure and usually have small rootwards. Racked members are the smallest logs with a wide range of sizes. These logs are generally the only visible logs after construction. Racked members reduce permeability to enhance flow deflection (Abbe et al., 2002).

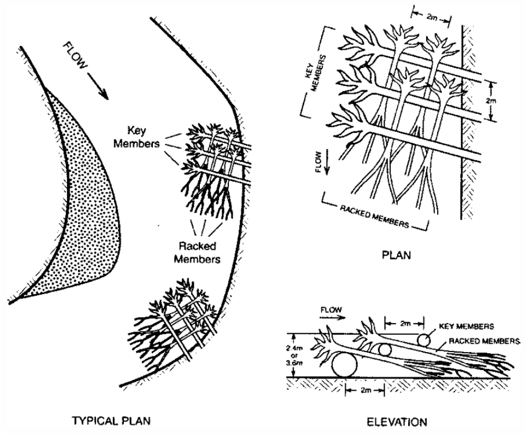


Figure 3.4: Typical plan view of an ELJ, by (Shields et al., 2004) based on the design by (Drury et al., 1999). Not that stacked members are here called racked members.

The main goal of an ELJ is to accelerate the natural process of a river CEM stage to reach equilibrium (stages IV and/or V). This implies that ELJ are best suited for incised sand bed channels. It achieves this by capturing sediment and debris to enhance the evolution of berms. Shields et al. (2004) mentions that the first step to designing an ELJ is that the main body should resist flotation. Secondly the density of the main body should reduce velocities and turbulence enough to allow sediment to deposit and retain debris. Due to the natural decay of wood the structure should encourage the development of vegetation in order to remain stable. A summary of design criteria for bank stabilisation using ELJs is given in table 3.1.

The geometry of an ELJ can be specified using four parameters (Shields et al., 2004): crest angle, length, elevation and spacing. The crest angle should not be larger than 30° to reduce erosion of the (mid)channel, see 3.1. These angles are still sufficient to deflect flows. The crest length can be set to the current equilibrium width of the channel times the cosine of the angle (Downs and Simon, 2001), or to a desired conveyance width. Crest elevation should be high enough such that the berms that develop will stabilise the bank. If this is not the case instabilities of the bank can still occur, leading to failure and regression of the bank. The required crest elevation can be obtained from bank stability analysis or rules of thumb (Darby and Simon,

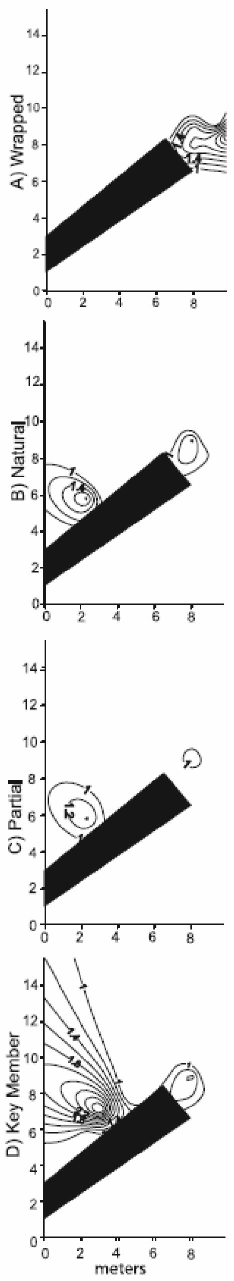


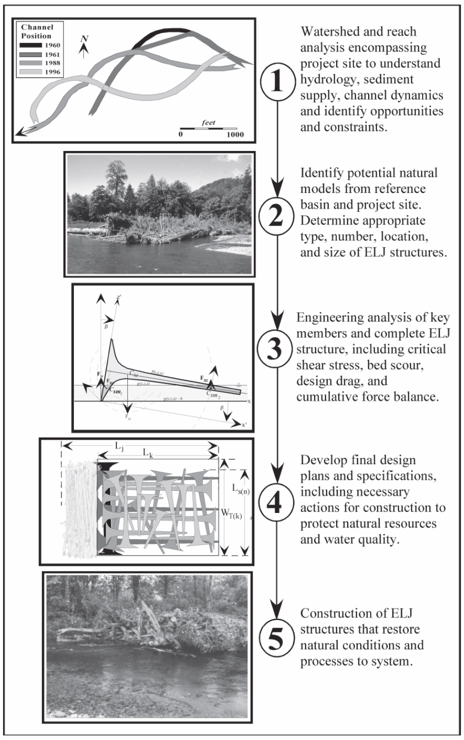
Figure 3.3: Excess shear stress for jam 2. Flow from South to North.

1999; Shields et al., 1995). Spacing of ELJs depends on the area of influence. This area is affected by the flow separation zone that extends from the downstream tip of the structure. ELJ can be assumed to function as groins. Petersen (1986) states that the spacing should be 1.5-2.0 times the crest length. However Drury et al. (1999) found that a spacing of approximately 5 times the crest length is still effective, a similar value to groins. The crest length of groins is significantly smaller than of ELJs (half or less) and therefor when using ELJs less structures are required to stabilise a bank section. This reduces construction costs.

| Category | Specific criteria |
|---|---|
| Economic | Cost per unit length of bank treated must be less than cost for traditional stone structures |
| Environmental | Materials must be locally available components of lightly degraded or pristine regional stream corridor ecosystems |
| | Structures must contribute to and accelerate natural recovery of riparian zone habitats and plant communities |
| | Measures must address key impairments in aquatic habitat: shortage of pool habitats, woody debris, and stable substrate |
| Structural | Structures should withstand the 5-year return interval flow without failure |
| Hydraulic | Structures should trap and retain sand-size sediments |
| | Flood stages may be increased, but duration of overbank flooding during the growing season should not be significantly increased |
| | Structures should be sized to promote berm formation that creates a two-stage compound channel with width and depth relative to watershed area similar to stable Stage V or VI channels within the region |
| Geotechnical | Some additional mass wasting of near-vertical banks is allowed, but structures should trap and retain materials resulting from bank caving. Structures should be high enough so that bank heights will be reduced to stable levels when structures are filled with sediments |
| Construction | Minimal requirements for specialized training and equipment |
| | Structures should be constructed using equipment operating from within the channel with minimal additional clearing and disturbance required |

Table 3.1: ELJ design criteria for bank stabilisation by Shields et al. (2004) for Little Topashaw Creek. Structural and Construction design criteria can be adjusted accordingly.

Abbe et al. (2002) presented a design process for ELJs, figure 3.5. The design process starts with an analysis of the stream region. It is important to first understand the origin of the behaviour of a stream and to define opportunities and limitations. The second step is to determine the general dimensions of the ELJs based on natural models. Where should the ELJ be located, how many ELJs should be implemented and what are their respective sizes. Once this is known, the third step is initiated. Key members of each ELJ are designed based on a force balance. The fourth step finalises the design with stacked and racked members to add functionality and structural integrity. The ELJs are then constructed at the specified location in step five.



Watershed and reach analysis encompassing project site to understand hydrology, sediment supply, channel dynamics and identify opportunities and constraints.

Identify potential natural models from reference basin and project site. Determine appropriate type, number, location, and size of ELJ structures.

Engineering analysis of key members and complete ELJ structure, including critical shear stress, bed scour, design drag, and cumulative force balance.

Develop final design plans and specifications, including necessary actions for construction to protect natural resources and water quality.

Construction of ELJ structures that restore natural conditions and processes to system.

Figure 3.5: Five basic designs steps for implementation of ELJs (Abbe et al., 2002).

Choosing the right type of ELJ is vital to its success. An ELJ can be designed to be stable under the most extreme conditions, however if the type of ELJ does not reflect its purpose the acquired results can be undesirable. Abbe et al. (2002) provided a flow chart to determine which type of ELJ should be used for what type of channel instability, see figure 3.6. They can be categorised into two main categories, grade control (channel incision) and flow manipulation (channel migration). Grade control includes Step and Valley jams that capture sediment and woody debris, creating (large) steps in the stream. These types can be used to counter channel incision because of the high retention properties. Flow manipulation types consist of two subcategories, bank protection and flow diversion. Bank protection includes Bench and Flow Deflection jams. These types deflect flows away from stream banks, thus having a stabilisation effect. Over time, when the bank is accreted, the structures are integrated with the bank and will then act as bank protection. Flow diversion includes Bar Apex and Meander jams. These types are found in low gradient streams. Bar Apex jams can create mid channel bars on which vegetation can grow. Meander jams are found to perform really well in limiting stream migration, bank protection and restoration of aquatic and riparian habitat. Examples of all six jam types can be found in appendix J.

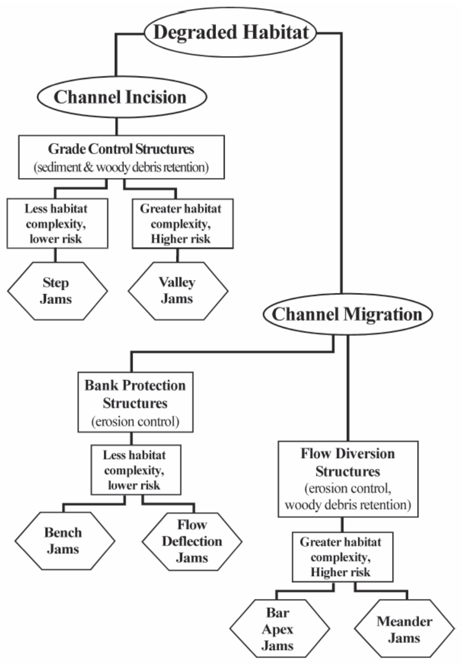


Figure 3.6: ELJ classification flow chart (Abbe et al., 2002).

## 3.3 Engineered Log Jam for bank protection

As mentioned in the sections above the main mechanism of an ELJ is the reduction of local flow velocities and deflection of flow direction away from stream banks. Previous studies cited in this report focused on the effect of ELJ on bed elevations. The effect of ELJ on the flow (hydraulic impact) has been tested in multiple flume experiments. An ELJ model, adopted from Brooks et al. (2006) (similar to the typical plan from figure 3.4), has been tested by Gallisdorfer et al. (2014). Two types of ELJs were tested on a fixed and move-able bed, see figure 3.7. The first ELJ resembles a perpendicular deflector jam, the second a spur dike (oblique deflector jam). From the fixed bed experiments, figure 3.8, the effect of an ELJ on the flow velocities are mapped. The oblique orientation of ELJ-2 reduces the blockage effect of the structure, reducing flow acceleration along the structure compared to ELJ-1. The normalised time-averaged downstream velocity v/<v> for ELJ-1 is larger than 1.5, for ELJ-2 this is smaller than 1.5. Also directly behind the structures both ELJs created low flow velocity zones. Gallisdorfer et al. (2014) also mentions the presence of a vertical mixing layer, approximately half the blockage width of the structure.

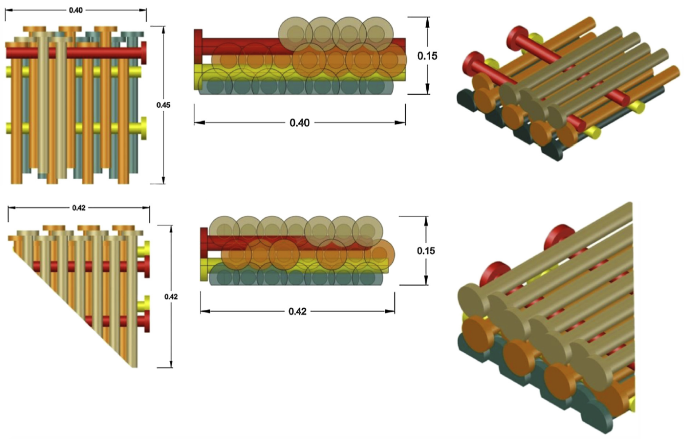


Figure 3.7: (Top) ELJ-1: perpendicular deflector jam (bottom) ELJ-2: spur dike deflector jam

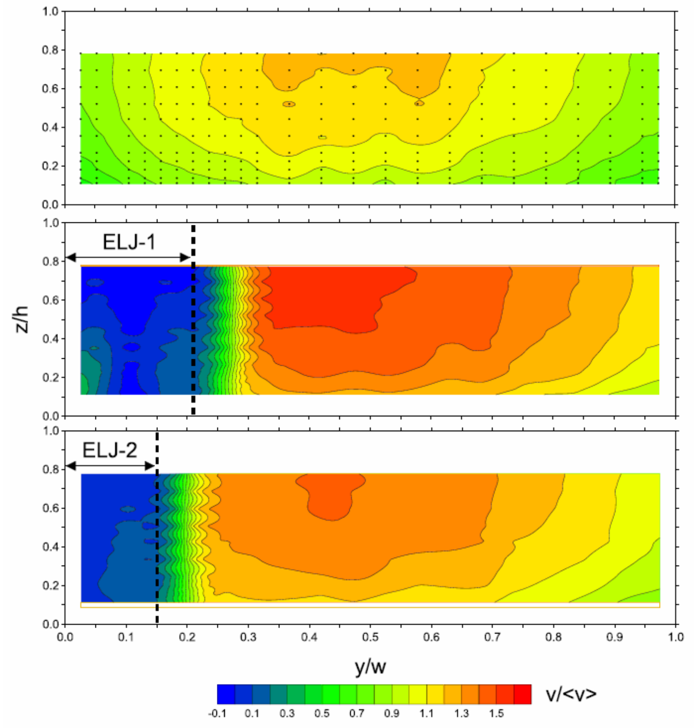


Figure 3.8: Contour maps of normalised time-average 0.1m downstream velocity $v/<v>$, normalised height $z/h$ and normalised width $y/w$. From top to bottom: clear water flow, ELJ-1, ELJ-2. Vertical dashed lines indicate blockage width of the ELJ.

Only ELJ-1 was used for the experiment with a move-able bed. From aerial photography a Digital Elevation Model (DEM) is created from which erosion and deposition is quantified. The results are shown in figure 3.9. Net erosion is seen from the leading edge of the ELJ up to the end of the experimental channel area. Deposition is located directly downstream of the eroded area. The bank downstream of the ELJ remains unchanged or little erosion, again showing the bank stabilising effect of an ELJ. However, surprisingly the opposite bank shows erosion of the bank and aggregation of the bank toe. This suggests that the influence area of an ELJ extends far beyond its own in flow dimensions. Analysing the opposite bank in figure 3.8 the surface flow velocities are slightly increased or decreased. The bed flow velocities are decreased. This somewhat strengthens the suggestion that an ELJ has a larger area of influence than its in flow dimensions.

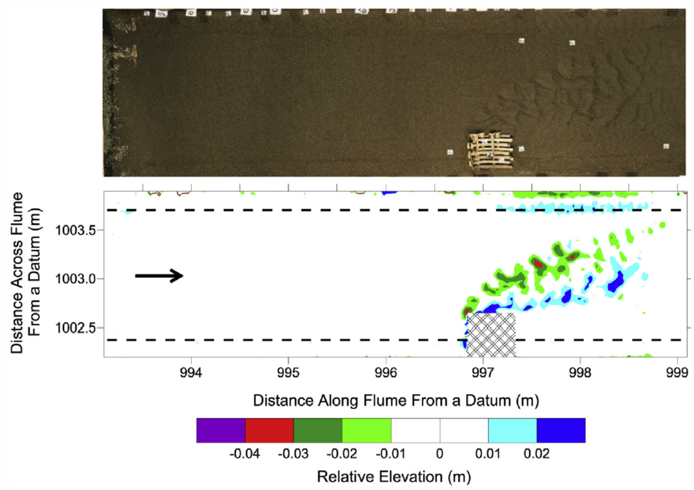


Figure 3.9: Aerial photography (top) and DEM (bottom). Negative values indicate net erosion, positive values net deposition. The dashed lines indicate the toe of the banks of the trapezoidal channel. Arrow indicates flow direction and textured box ELJ.

Further research is done by S.J. Bennett and S. Mohammad Ghaneeizad and M.S. Gallisdorfer and D. Cai and J.F. Atkinson and A.S. and E.J. Langendoen (2015). In this study the same ELJs were used, with a fixed bed, but also with one or more structures in series. Their reference experiment shows similar results as Gallisdorfer et al. (2014), see appendix H figure H.1. Turbulence parameters $U_{rms}$, $V_{rms}$ and $W_{rms}$ were also measured (equation 3.1, $x = \overline{x} + x'$. Upstream of the ELJs no differences in these parameters were measured. However downstream of the structures these parameters are significantly increased in the mixing layer, figures H.2 to H.4. As well as decreased directly behind the structures. The turbulent kinetic energy is only shown here, figure 3.10. Despite these changes in turbulence, the overall magnitude (equation 3.2, $< x >$ is the average) of the flow did not change (S.J. Bennett and S. Mohammad Ghaneeizad and M.S. Gallisdorfer and D. Cai and J.F. Atkinson and A.S. and E.J. Langendoen, 2015). This was also observed in the field by Daniels and Rhoads (2003); Manners et al. (2007).

$$u_{rms} = \sqrt{\overline{u'^2}} \qquad v_{rms} = \sqrt{\overline{v'^2}} \qquad w_{rms} = \sqrt{\overline{w'^2}} \qquad k = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \tag{3.1}$$

$$U_{mag} = \sqrt{\langle u\rangle^2 + \langle v\rangle^2 + \langle w\rangle^2} \tag{3.2}$$

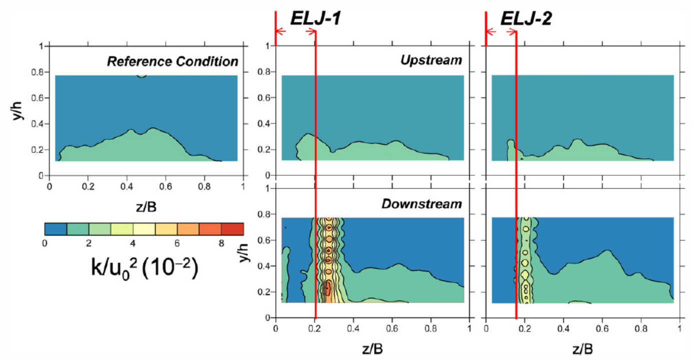


Figure 3.10: Contour plots of normalised time-averaged downstream velocity. The reference condition map (left) shows the flow field without any structures present. The additional maps show ELJ-1 (middle) and ELJ-2 (right) for the upstream (top) and downstream (bottom) cross sections. Red lines indicate in flow widths of the ELJs.

The bed shear stresses are shown in figure 3.11. Three bed shear stresses are defined: $\tau_u$ the well known bed shear stress based on shear velocity; $\tau_R$ is based on Reynolds stress and $\tau_k$ on the turbulent kinetic energy.

Definitions are given in equation 3.3. Across the ELJ structure the bed shear stresses are reduced to roughly 50% of the reference condition. Just next to the ELJ structure, at the location of the mixing layer, the bed shear stresses are greatly increased, up to eight times the reference condition. This corresponds with the locations of erosion observed by Gallisdorfer et al. (2014).

$$\tau_u = \rho u_*^2 \qquad \tau_R = -\rho\overline{u'v'}|_{y=0} \qquad \tau_k = ck|_{y=0} \tag{3.3}$$

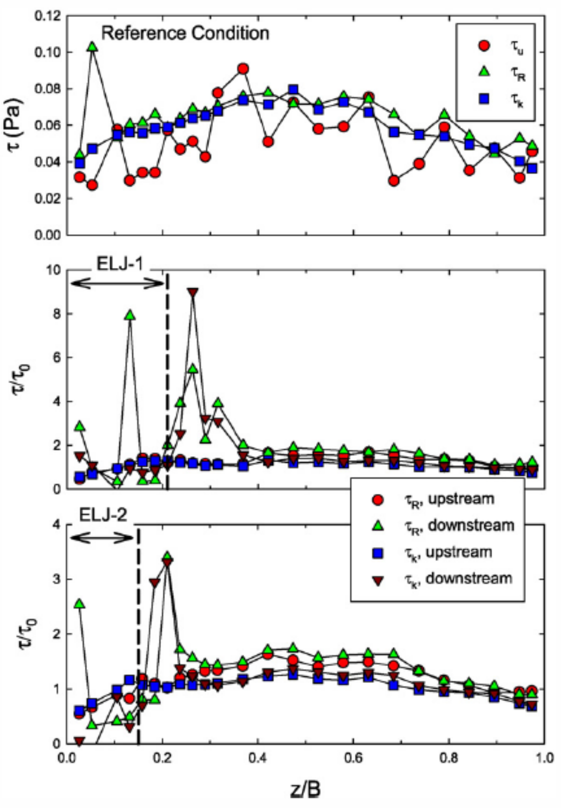


Figure 3.11: Transverse distributions of bed shear stress. Reference condition (top), ELJ-1 (middle) and ELJ02 (bottom). The reference conditions uses values, the ELJs use normalised values.

A series of structures effects stream hydraulics differently than a single structure. Therefor S.J. Bennett and S. Mohammad Ghaneeizad and M.S. Gallisdorfer and D. Cai and J.F. Atkinson and A.S. and E.J. Langendoen (2015) also did experiments with two and three structures in series, with different spacing. Figures for two structures are shown in appendix H. The effect was quantified by spatially averaging the downstream flow velocity of the downstream structure, and then normalised using the spatially averaged upstream flow velocity of the upstream structure (columns 2 and 4, rows 2-4 are normalised using row 1 in figures H.5 and H.6). The quantification is shown in figure 3.12. The normalised downstream velocity $V^*$ is reduced up to 80%, yet the normalised turbulent kinetic energy $K^*$ acts differently. For a spacing of 7.5h it is reduced to 50%, while at 15h no reduction is measured and at 30h it is grown to roughly 200%. When the spacing is larger than 7.5h the disturbed flow of the first structure has an increased influence on the near field region. The velocity structure extends nearer to the wall and shows a vertical structure. The turbulent kinetic energy also extends nearer to the wall. This analysis suggests that the wake region (region of disturbed flow) extends beyond 30h (7.5 times the crest length), because the flow does not return to reference conditions. To conclude this study strengthens the validity of using ELJs as bank protections.

The last note to be made about the study by S.J. Bennett and S. Mohammad Ghaneeizad and M.S. Gallisdorfer and D. Cai and J.F. Atkinson and A.S. and E.J. Langendoen (2015) is that they measured drag coefficients $C_D$ between 1 and 3. These values could be used in numerical models to model the effect of ELJs on morphodynamic responses of river channels.

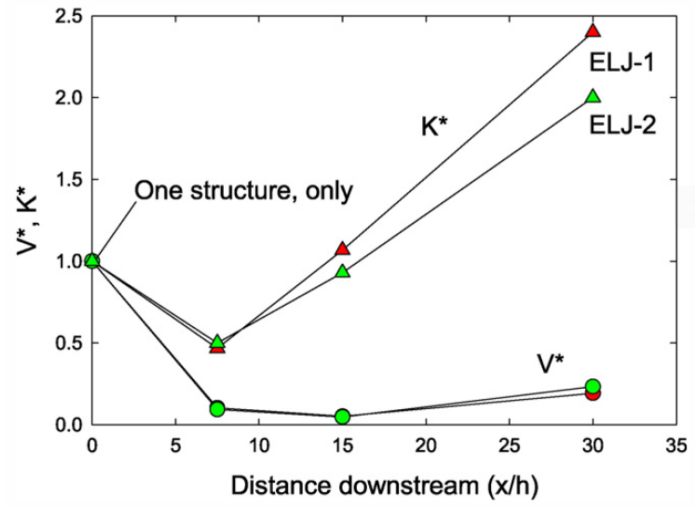


Figure 3.12: Spatially averaged near-field downstream velocity $V^*$ and turbulent kinetic energy $K^*$ determined upstream of the ELJs, and normalised by the values observed for a single structure. On the horizontal axis the downstream distance correspond with the spacing.

The shape of an ELJ strongly affects the hydraulic impact and thus the morphological response of a stream. This has been studied by Svoboda and Russell (2011). Six configurations (figures I.1 to I.6) were fixed in location and erosion quantities were measured. All results are shown in appendix I. Table 3.2 summarises the results. The results display the contour map after the experiments had run six hours. Erosion and deposition smaller than the used grain size were ignored. Here only the results from configuration 2 are shown for consistency with the previous sections of this chapter. Similarly to the results of Gallisdorfer et al. (2014), erosion occurs at the leading edge of the ELJ and extending to the channel centre. Deposition occurs behind the trailing edge of the ELJ, and centre channel deposition occurs directly downstream of the eroded area.

Figure 2. Configuration 1: Triangular LWD structure.

Figure 3. Configuration 2: Rectangular LWD structure.

Figure 4. Configuration 3: LWD Cross-structure with downstream log on top.

Figure 5. Configuration 4: LWD Cross-structure with upstream log on top.

Figure 6. Configuration 3: Free-form LWD structure.

Figure 7. Configuration 6: Bar Apex Jam LWD structure.

Figure 3.13: All six configurations used in the study from (Svoboda and Russell, 2011).

The triangular ELJ (configuration 1) creates erosion and deposition closer to the bank due to less flow deflection. The cross structures are different in their contour maps due to log elevations. Where the downstream log is on top erosion occurs within the ELJ structure. With the upstream log on top, erosion occurs at the upstream tip of the downstream log and some deposition is found within the ELJ. The free-form structure shows erosion at each downstream oriented rootward. Near the bank a large area of erosion was found, likely due to flow deflection of the upstream oriented log. The free-form structure also has the largest volume and area of erosion and deposition. The bar apex jam type ELJ showed the least amount of scour, however scour was present very close to the bank. Also deposition occurred the furthest downstream of all structures (Svoboda and Russell, 2011).

| Configuration number | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Percent of channel width obstructed (%) | 35.1 | 47.7 | 35.1 | 35.1 | 47.3 | 44.4 |
| Volume of scour (ft$^3$) | 0.78 | 0.88 | 1.76 | 1.35 | 1.94 | 0.52 |
| Volume of deposition (ft$^3$) | 0.60 | 1.02 | 1.51 | 1.13 | 1.85 | 0.29 |
| Surface area of scour (ft$^2$) | 15.47 | 23.41 | 16.94 | 14.16 | 26.86 | 7.23 |
| Surface area of deposition (ft$^2$) | 8.06 | 11.87 | 13.56 | 13.32 | 13.89 | 7.93 |

Table 3.2: Results from (Svoboda and Russell, 2011). All results for 90% bankfull width simulation.

Overall, tightly constructed ELJs (config. 1 and 6) produce the least amount of scour volume. Configurations 1, 2 and 5 produced several small scour zones, while configurations 3 and 4 produce one large scour and deposition area. Moreover, upstream oriented logs strongly deflect flows aiding in directing regions of scour (Svoboda and Russell, 2011). The obstructed channel width for all configurations was roughly the same (35%-48%). Combined with the results, it can be concluded that the three dimensional shape of an ELJ has a larger influence than its obstruction.

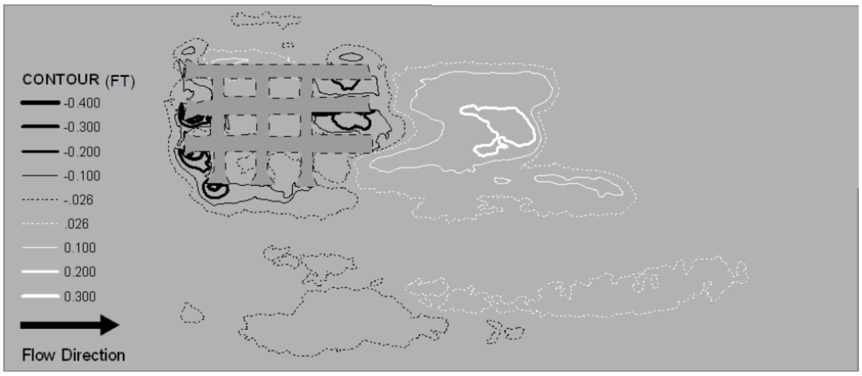


Figure 3.14: Configuration 2: Rectangular structure contour map

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# A | River Continuum Concept effects

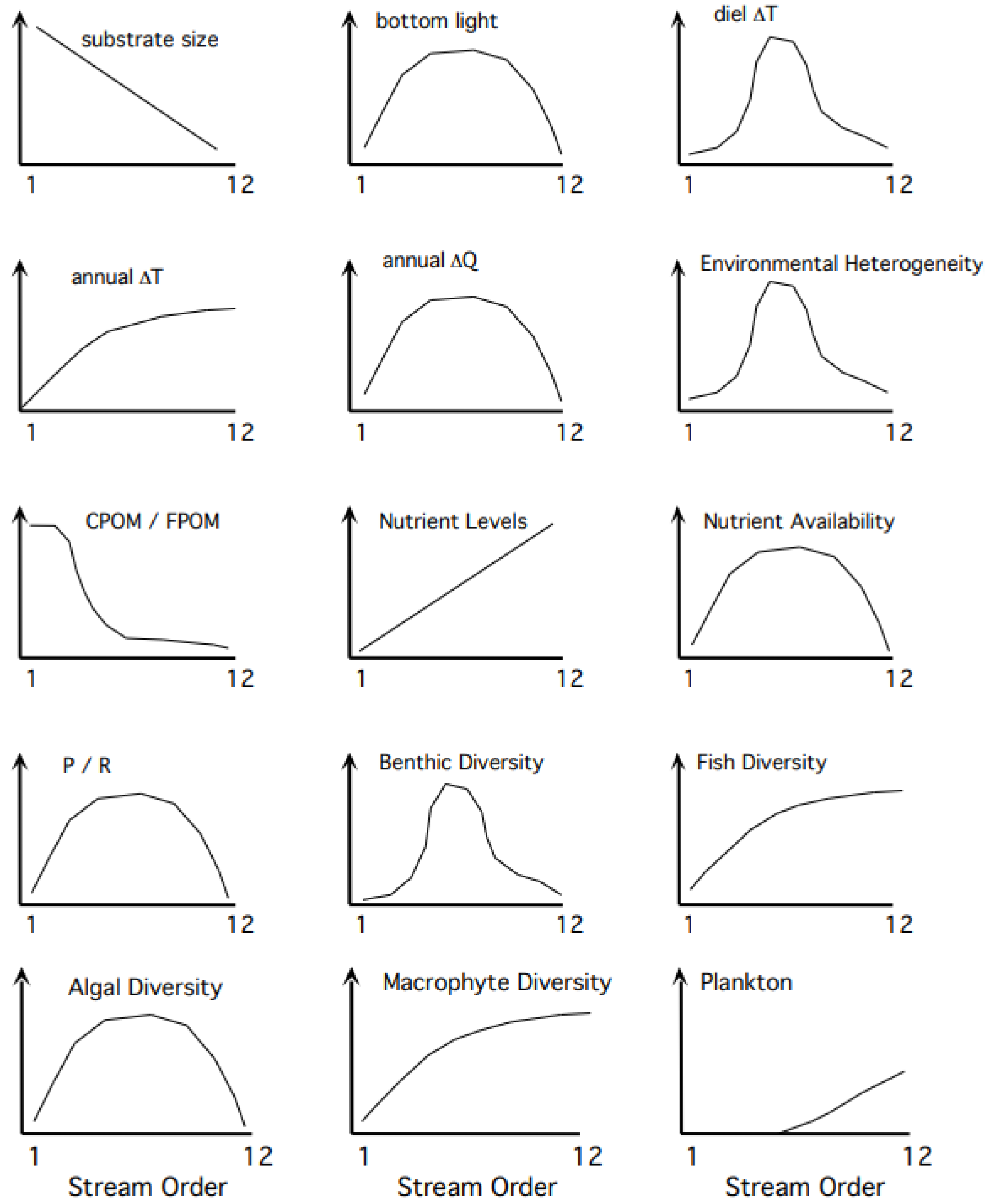


Figure A.1: River Continuum Concept effects

# B | Link Discontinuity Concept effects

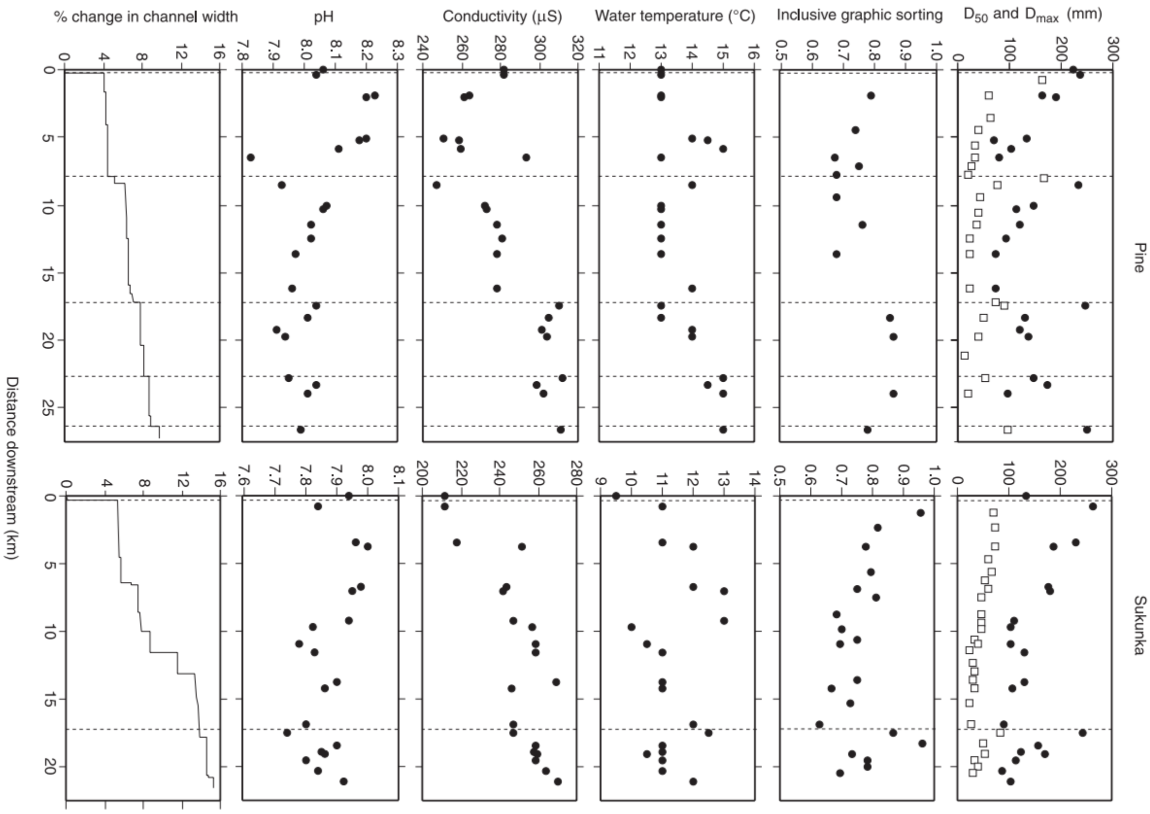


Figure B.1: Link Discontinuity Concept effects

# C | Urban Channel Evolution Model

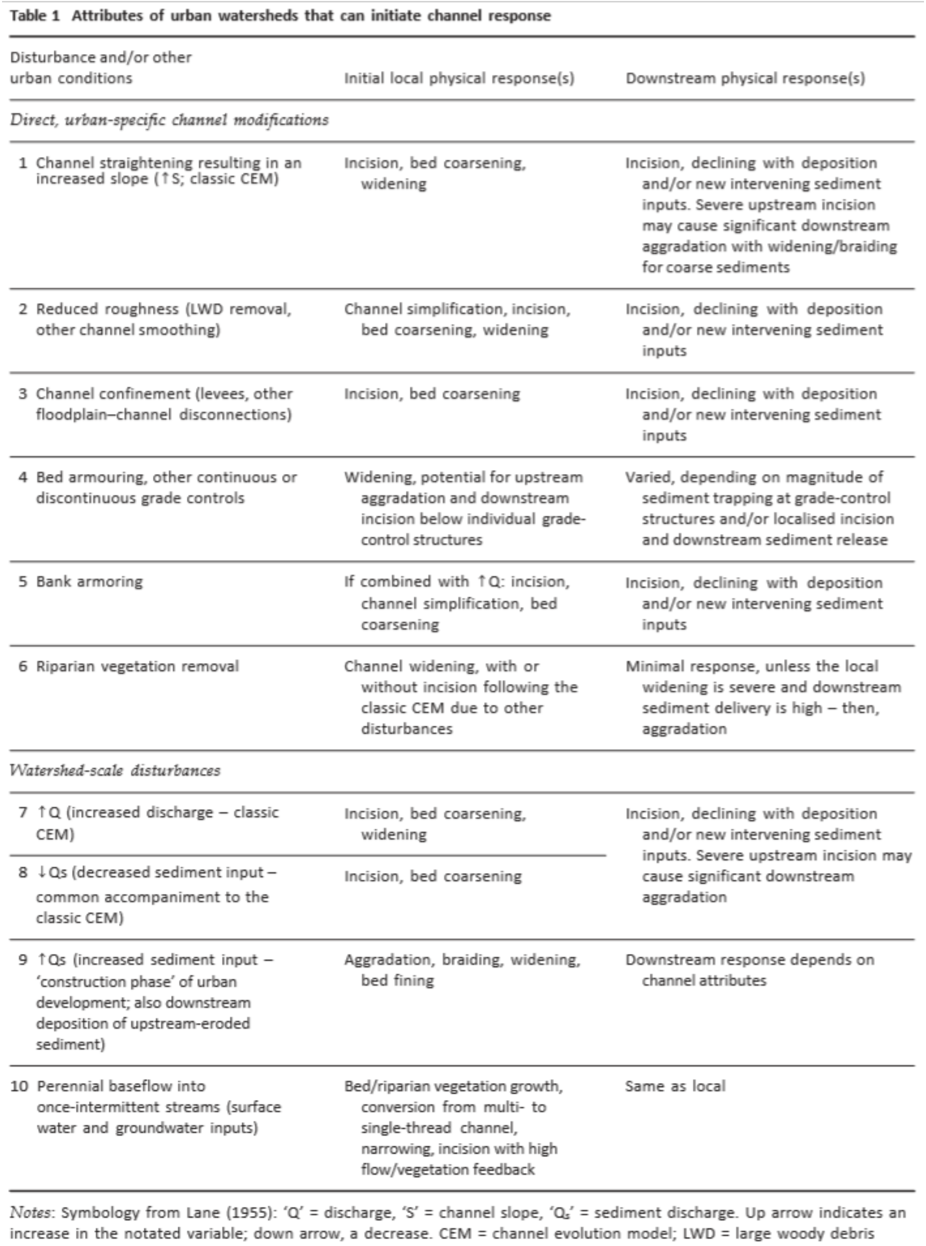
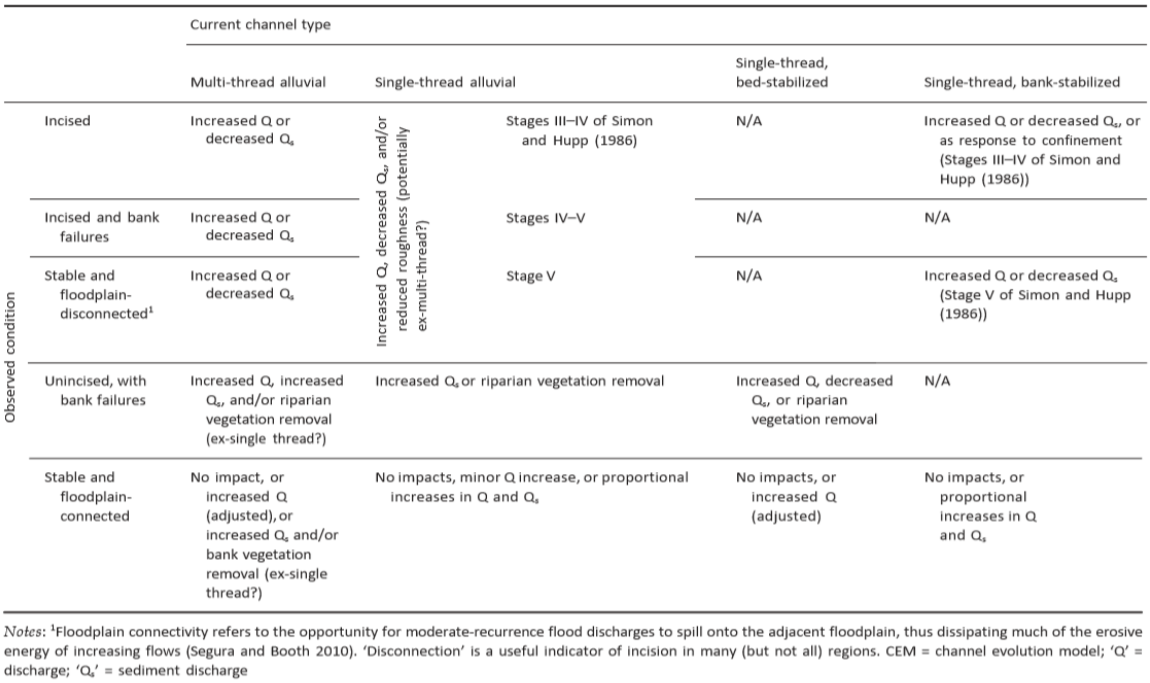


**Table 1 Attributes of urban watersheds that can initiate channel response**

| Disturbance and/or other urban conditions | Initial local physical response(s) | Downstream physical response(s) |
|---|---|---|
| *Direct, urban-specific channel modifications* | | |
| 1 Channel straightening resulting in an increased slope (↑S; classic CEM) | Incision, bed coarsening, widening | Incision, declining with deposition and/or new intervening sediment inputs. Severe upstream incision may cause significant downstream aggradation with widening/braiding for coarse sediments |
| 2 Reduced roughness (LWD removal, other channel smoothing) | Channel simplification, incision, bed coarsening, widening | Incision, declining with deposition and/or new intervening sediment inputs |
| 3 Channel confinement (levees, other floodplain–channel disconnections) | Incision, bed coarsening | Incision, declining with deposition and/or new intervening sediment inputs |
| 4 Bed armouring, other continuous or discontinuous grade controls | Widening, potential for upstream aggradation and downstream incision below individual grade-control structures | Varied, depending on magnitude of sediment trapping at grade-control structures and/or localised incision and downstream sediment release |
| 5 Bank armoring | If combined with ↑Q: incision, channel simplification, bed coarsening | Incision, declining with deposition and/or new intervening sediment inputs |
| 6 Riparian vegetation removal | Channel widening, with or without incision following the classic CEM due to other disturbances | Minimal response, unless the local widening is severe and downstream sediment delivery is high – then, aggradation |
| *Watershed-scale disturbances* | | |
| 7 ↑Q (increased discharge – classic CEM) | Incision, bed coarsening, widening | Incision, declining with deposition and/or new intervening sediment inputs. Severe upstream incision may cause significant downstream aggradation |
| 8 ↓Qs (decreased sediment input – common accompaniment to the classic CEM) | Incision, bed coarsening | |
| 9 ↑Qs (increased sediment input – 'construction phase' of urban development; also downstream deposition of upstream-eroded sediment) | Aggradation, braiding, widening, bed fining | Downstream response depends on channel attributes |
| 10 Perennial baseflow into once-intermittent streams (surface water and groundwater inputs) | Bed/riparian vegetation growth, conversion from multi- to single-thread channel, narrowing, incision with high flow/vegetation feedback | Same as local |

*Notes*: Symbology from Lane (1955): 'Q' = discharge, 'S' = channel slope, '$Q_s$' = sediment discharge. Up arrow indicates an increase in the notated variable; down arrow, a decrease. CEM = channel evolution model; LWD = large woody debris

Figure C.1: Urban Channel Evolution Model Disturbances



| | | Current channel type | | | | |
|---|---|---|---|---|---|---|
| | | Multi-thread alluvial | Single-thread alluvial | | Single-thread, bed-stabilized | Single-thread, bank-stabilized |
| Observed condition | Incised | Increased $Q$ or decreased $Q_s$ | Increased $Q$, decreased $Q_s$, and/or reduced roughness (potentially ex-multi-thread?) | Stages III–IV of Simon and Hupp (1986) | N/A | Increased $Q$ or decreased $Q_s$, or as response to confinement (Stages III–IV of Simon and Hupp (1986)) |
| | Incised and bank failures | Increased $Q$ or decreased $Q_s$ | | Stages IV–V | N/A | N/A |
| | Stable and floodplain-disconnected[1] | Increased $Q$ or decreased $Q_s$ | | Stage V | N/A | Increased $Q$ or decreased $Q_s$ (Stage V of Simon and Hupp (1986)) |
| | Unincised, with bank failures | Increased $Q$, increased $Q_s$, and/or riparian vegetation removal (ex-single thread?) | Increased $Q_s$ or riparian vegetation removal | | Increased $Q$, decreased $Q_s$, or riparian vegetation removal | N/A |
| | Stable and floodplain-connected | No impact, or increased $Q$ (adjusted), or increased $Q_s$ and/or bank vegetation removal (ex-single thread?) | No impacts, minor $Q$ increase, or proportional increases in $Q$ and $Q_s$ | | No impacts, or increased $Q$ (adjusted) | No impacts, or proportional increases in $Q$ and $Q_s$ |

*Notes*: [1] Floodplain connectivity refers to the opportunity for moderate-recurrence flood discharges to spill onto the adjacent floodplain, thus dissipating much of the erosive energy of increasing flows (Segura and Booth 2010). 'Disconnection' is a useful indicator of incision in many (but not all) regions. CEM = channel evolution model; '$Q$' = discharge; '$Q_s$' = sediment discharge

Figure C.2: Urban Channel Evolution Model Diagnostic

# D | Large Woody Debris Index

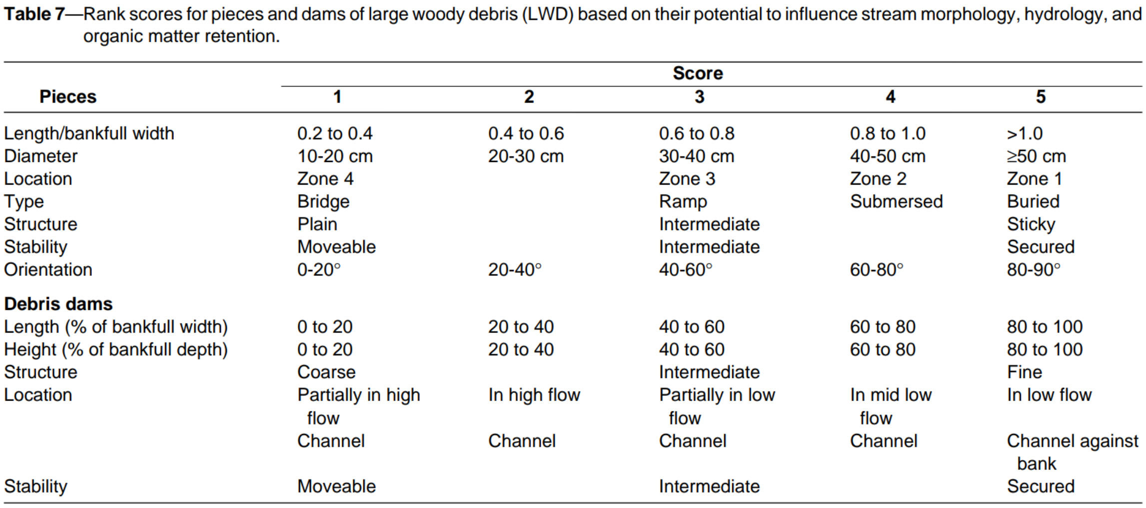


**Table 7**—Rank scores for pieces and dams of large woody debris (LWD) based on their potential to influence stream morphology, hydrology, and organic matter retention.

| | Score | | | | |
|---|---|---|---|---|---|
| **Pieces** | **1** | **2** | **3** | **4** | **5** |
| Length/bankfull width | 0.2 to 0.4 | 0.4 to 0.6 | 0.6 to 0.8 | 0.8 to 1.0 | >1.0 |
| Diameter | 10-20 cm | 20-30 cm | 30-40 cm | 40-50 cm | ≥50 cm |
| Location | Zone 4 | | Zone 3 | Zone 2 | Zone 1 |
| Type | Bridge | | Ramp | Submersed | Buried |
| Structure | Plain | | Intermediate | | Sticky |
| Stability | Moveable | | Intermediate | | Secured |
| Orientation | 0-20° | 20-40° | 40-60° | 60-80° | 80-90° |
| **Debris dams** | | | | | |
| Length (% of bankfull width) | 0 to 20 | 20 to 40 | 40 to 60 | 60 to 80 | 80 to 100 |
| Height (% of bankfull depth) | 0 to 20 | 20 to 40 | 40 to 60 | 60 to 80 | 80 to 100 |
| Structure | Coarse | | Intermediate | | Fine |
| Location | Partially in high flow<br>Channel | In high flow<br>Channel | Partially in low flow<br>Channel | In mid low flow<br>Channel | In low flow<br>Channel against bank |
| Stability | Moveable | | Intermediate | | Secured |

Figure D.1: Large Woody Debris Index Criteria

# E | Stability of logs

**Logs without rootward** A force balance was used to determine log stability and entrainment depth. Right angle cylinders were used as a model for logs. Motion of the log was simplified to only sliding and no pivoting. The lift force was not included as the log were not fully submerged and therefore negligible. All forces acted on the centre of mass. A visual representation is shown in figure E.1.

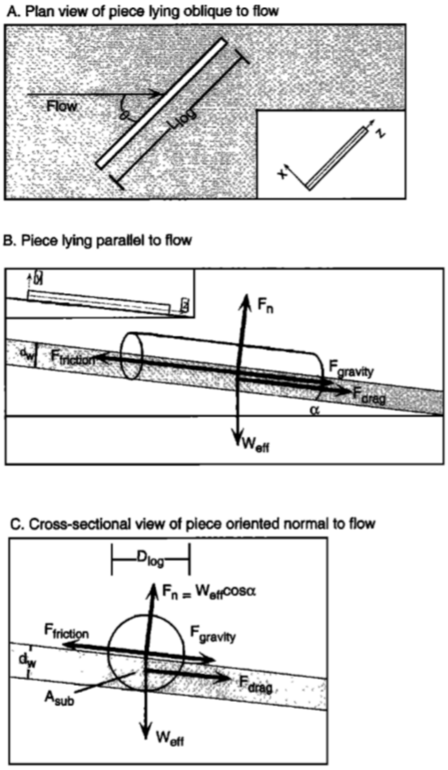


Figure E.1: Schematic representation of the forces considered to act on the logs without rootward. Coordinate system shown were used to determine log volume, not for force balance.

The equation to determine the forces are listed below:

$$F_{gravity} = W_{eff}\sin\alpha = -\left(g\rho_{log}L_{log}\frac{\pi D_{log}^2}{4} - g\rho_w L_{log}A_{sub}\right)\sin\alpha \tag{E.1}$$

$$F_{friction} = F_n\mu_{bed} = \left(g\rho_{log}L_{log}\frac{\pi D_{log}^2}{4} - g\rho_w L_{log}A_{sub}\right)\mu_{bed}\cos\alpha \tag{E.2}$$

$$F_{drag} = -\frac{U^2}{2}\rho_w C_D(L_{log}d_w\sin\theta + A_{sub}\cos\theta) \tag{E.3}$$

The force balance is $F_{friction} + F_{gravity} = F_{drag}$, leading to:

$$\left(g\rho_{log}L_{log}\frac{\pi D_{log}^2}{4} - g\rho_w L_{log}A_{sub}\right)(\mu_{bed}\cos\alpha - \sin\alpha) = \frac{U^2}{2}\rho_w C_D(L_{log}d_w\sin\theta + A_{sub}\cos\theta) \tag{E.4}$$

**Logs with rootward** For a log with a rootward the buoyant force is and portion of the log exposed to flow are reduced, figure E.2.

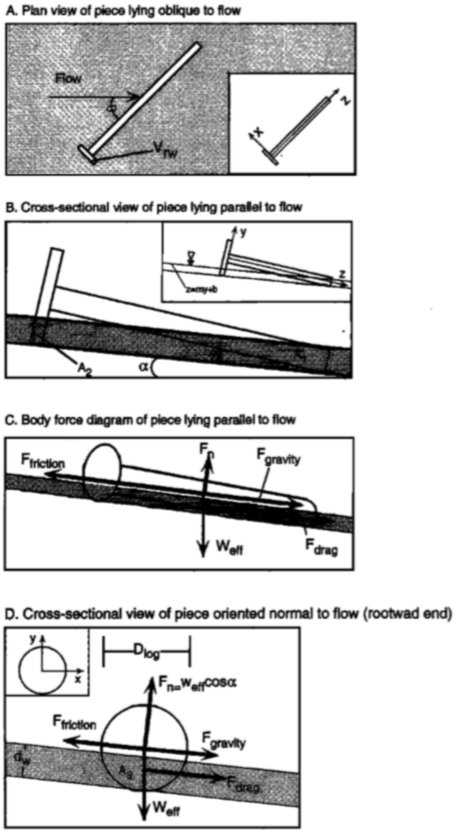


Figure E.2: Schematic representation of the forces considered to act on the logs with rootward. Coordinate system shown were used to determine log volume, not for force balance.

Defining a similar force balance leads to the changed equations listed below:

$$F_{gravity} = -\left[g\rho_{log}\left(L_{log}\frac{\pi D_{log}^2}{4} + V_{rw}\right) - g\rho_w(V_1 + V_2)\right]\sin\alpha \tag{E.5}$$

$$F_{friction} = \left[g\rho_{log}\left(L_{log}\frac{\pi D_{log}^2}{4} + V_{rw}\right) - g\rho_w(V_1 + V_2)\right]\mu_{bed}\cos\alpha \tag{E.6}$$

$$F_{drag} = -\frac{U^2}{2}\rho_w C_D[(A_1 + A_2)\sin\theta + A_3\cos\theta] \tag{E.7}$$

The force balance is $F_{friction} + F_{gravity} = F_{drag}$, leading to:

$$\left[g\rho_{log}\left(L_{log}\frac{\pi D_{log}^2}{4} + V_{rw}\right) - g\rho_w(V_1 + V_2)\right](\mu_{bed}\cos\alpha - \sin\alpha) = \frac{U^2}{2}\rho_w C_D[(A_1 + A_2)\sin\theta + A_3\cos\theta] \tag{E.8}$$

For definitions of $A_{sub}$ for logs without rootward and $A_1$ to $A_3$, $V_{rw}$, $V_1$, $V_2$ for logs with rootward the reader is referred to the original paper of Braudrick and Grant (2000).

The logs float when the buoyant force equals the weight of the log. For logs without rootward:

$$g\rho_{log} L_{log} \frac{\pi D_{log}^2}{4} = g\rho_w L_{log} A_{sub} \tag{E.9}$$

And for logs with rootward:

$$g\rho_{log} \left( L_{log} \frac{\pi D_{log}^2}{4} + V_{rw} \right) = g\rho_w (V_1 + V_2) \tag{E.10}$$

Braudrick and Grant (2000) analysed the proposed equations in their studies by plotting them with one changing variable (e.g. log length or diameter, water depth, log density etc.) for logs with and without rootwards. These figures can be viewed in their paper. Here only additional plots of their results are shown.

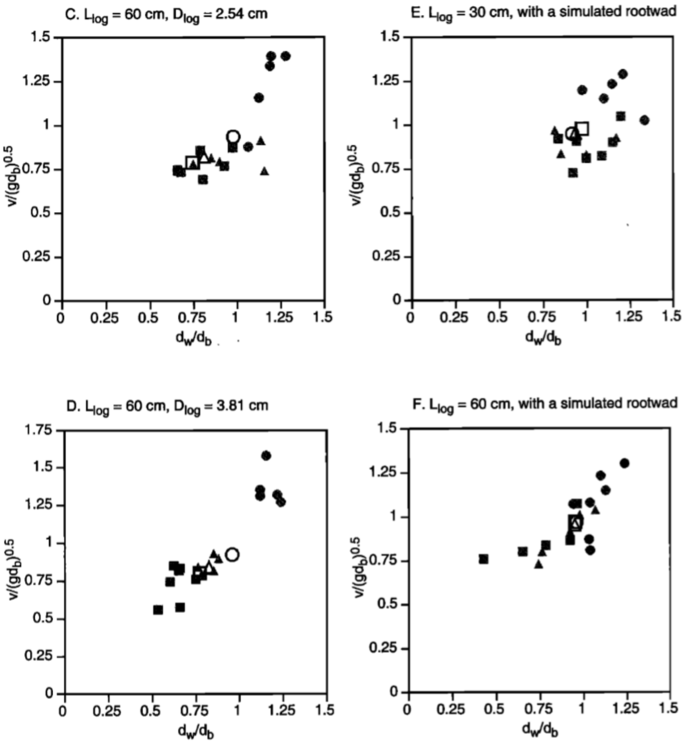


Figure E.3: Experimental results continued

A list of all used parameters, their definitions and values is given in table E.1:

| Parameter | Definition | Value |
|---|---|---|
| $A_1[m^2]$ | Submerged area bole | variable |
| $A_2[m^2]$ | Submerged area rootward | variable |
| $A_3[m^2]$ | Submerged area rootward perpendicular to piece length | variable |
| $A_{sub}$ | Submerged surface area perpendicular to piece length exposed to drag | variable |
| $C_d[-]$ | Drag coefficient | 1.05 (parallel) 0.8 (oblique) 1.0 (normal) |
| $D_{log}[m]$ | Log diameter | 0.0254-0.0381 |
| $D_{rw}[m]$ | Rootward diameter | 0.0508 |
| $d_w[m]$ | Flow depth | 0.018 |
| $g[m/s^2]$ | Gravitational acceleration | 9.81 |
| $L_{log}[m]$ | Piece length | 0.3-0.6 |
| $U[m/s]$ | Flow velocity | unspecified |
| $V_{rw}[m^3]$ | Rootward volume | variable |
| $V_1[m^3]$ | Submerged bole volume | variable |
| $V_2[m^3]$ | Submerged rootward volume | variable |
| $W_{eff}[kg]$ | Submerged weight | variable |
| $\alpha$[deg] | Bed angle in flow parallel plane | variable, equal to bed angle for low values |
| $\mu_{bed}[-]$ | Friction coefficient between wood and bed | 0.6 |
| $\rho_{log}[kg/m^3]$ | Density log | 435-736 |
| $\rho_w[kg/m^3]$ | Density water | unspecified |
| $\theta$[deg] | Piece angle relative to flow | variable, 0 when parallel to flow |

Table E.1: All parameters used in the equations

# F | Safety factor ballasted LWD structures

The safety factors were determined using a force balance. The considered forces are shown in figure F.1. The equations were defined for SLS first and modified for SLRWS and MLS. LWD was assumed to be fully submerged.

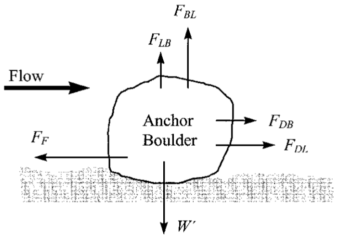


Figure F.1: Considered forces acting on an anchor boulder

The forces are defined as follows:

| | |
|---|---|
| $F_{BL}$ | Net buoyancy force acting on the LWD and transferred to the anchor boulder |
| $F_{DL}$ | Horizontal drag force acting on the LWD and transferred to the anchor boulder |
| $F_{DB}$ | Horizontal drag force acting directly on the anchor boulder |
| $F_{LB}$ | Vertical lift force acting directly on the anchor boulder |
| $W'$ | Immersed weight of the anchor boulder |
| $F_F$ | Frictional force at the base of the anchor boulder that resists sliding |

**SLS** The equations for these forces are defined as:

$$F_{BL} = 0.5L\frac{\pi D_L^2}{4}\rho g(1 - S_L) \tag{F.1}$$

$$F_{DL} = 0.5C_{DL}\rho\frac{V^2}{2}LD_L \sin\beta \tag{F.2}$$

$$F_{DB} = C_{DB}\rho\frac{V^2}{2}\frac{\pi D_B^2}{4} \tag{F.3}$$

$$F_{LB} = C_{DB}\rho\frac{V^2}{2}\frac{\pi D_B^2}{4} = 0.85F_{DB} \tag{F.4}$$

$$W' = \frac{\pi D_B^3}{6}\rho g(S_S - 1) \tag{F.5}$$

$$F_F = \left(W' - F_{BL} - \sum F_{LB}\right)\tanh\Phi \tag{F.6}$$

The factors of safety are defined with respect to sliding ($FS_S$) and with respect to buoyancy ($FS_B$):

$$FS_S = \frac{F_F}{F_{DL} + \sum F_{DB}} \qquad FS_B = \frac{\sum W'}{F_{BL} + \sum F_{LB}} \tag{F.7}$$

**SLRWS** The force $F_{BL}$ is modified for the influence of the rootward. Force $F_{DL}$ is replaced with $F_{DRW}$, the horizontal drag force transferred from LWD. The other four forces remain unchanged, equations F.3 to F.6.

$$F_{BL} = \left( \frac{\pi D_L^2 L}{4} + \frac{1}{3} \frac{\pi D_{RW}^2 L_{RW}}{4} (1-p) \right) \rho g (1 - S_L) \tag{F.8}$$

$$F_{DRW} = C_{DRW} \frac{\pi D_{RW}^2 L}{4} \frac{V^2}{2} \rho \sin\alpha \tag{F.9}$$

The factors of safety are defined with respect to sliding ($FS_S$) and with respect to buoyancy ($FS_B$), using equation F.8 for $F_{BL}$:

$$FS_S = \frac{F_F}{F_{DRW} + \sum F_{DB}} \qquad FS_B = \frac{\sum W'}{F_{BL} + \sum F_{LB}} \tag{F.10}$$

**MLS** Drag forces acting on the MLS are difficult to quantify, due to sheltering of LWD pieces within the structure. However structural stability is obtained through frictional resistance acting on the anchor boulders. The factor of safety against buoyancy is sufficient only when $F_{BL}$ from equation F.1 is calculated for each member of the MLS.

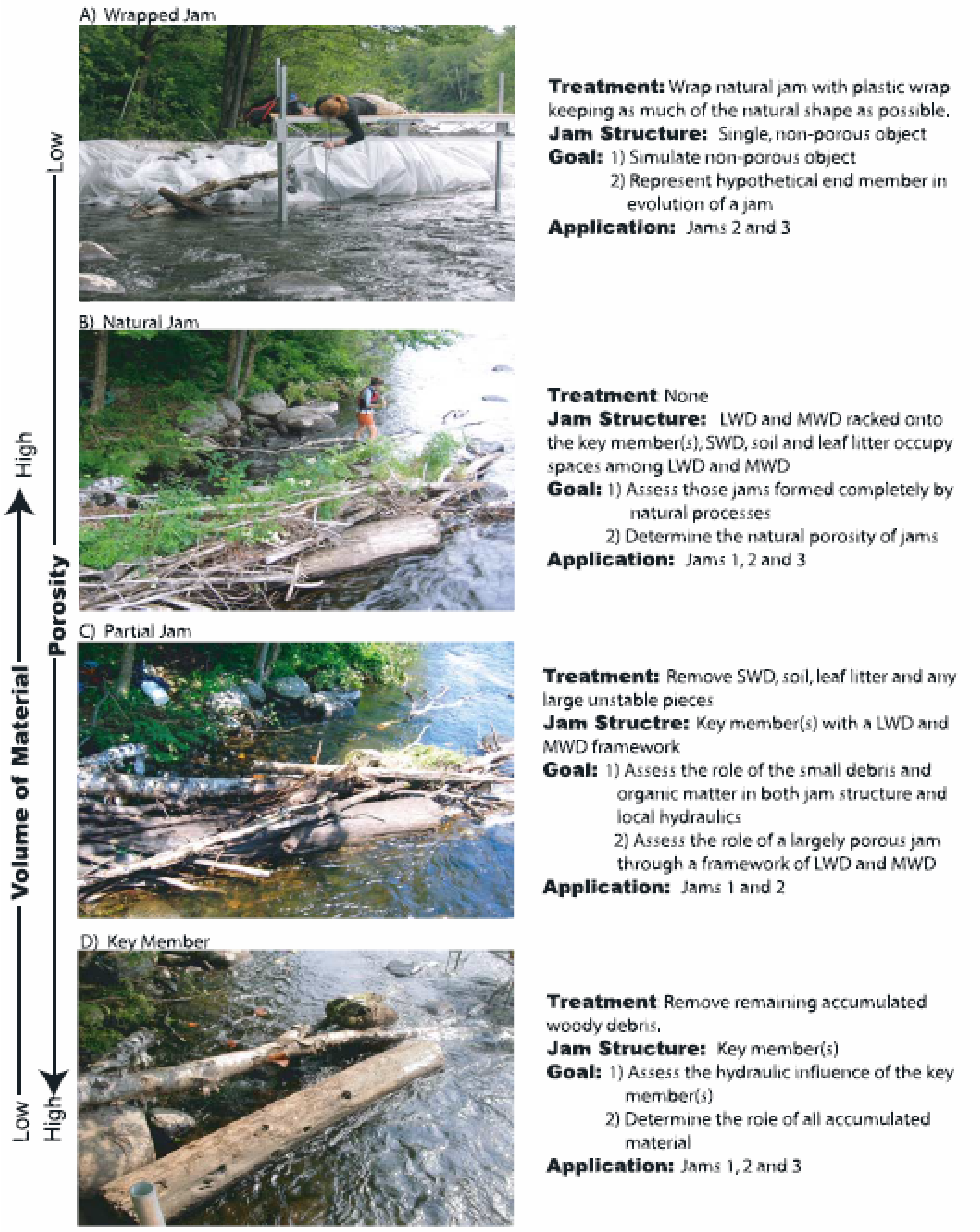
$$FS_B = \frac{\sum W'}{\sum F_{BL} + \sum F_{LB}} \tag{F.11}$$

A list of all used parameters, their definitions and values is given in table F.1:

| Parameter | Definition | Value |
|---|---|---|
| $C_{DL}[-]$ | Drag coefficient | 0.3 |
| $C_{DB}[-]$ | Drag coefficient | 0.4 |
| $C_{LB}[-]$ | Lift coefficient | 0.17 |
| $C_{DRW}[-]$ | Drag coefficient rootward | 1.2 |
| $D_L[m]$ | LWD piece mean diameter | variable |
| $D_{RW}[m]$ | Rootward mean diameter | variable |
| $D_B[m]$ | Anchor boulder mean diameter | variable |
| $g[m/s^2$ | gravitational acceleration | 9.81 |
| $\rho[kg/m^3]$ | Density of water | 1000 |
| $L[m]$ | LWD piece length (without rootward) | variable |
| $L_{RW}[m]$ | Rootward length | variable |
| $p[-]$ | Proportion of void space in rootward | 0.2 |
| $S_L[-]$ | Specific gravity of LWD | 0.5 (dry) 0.8-0.9 (wet) |
| $S_S[-]$ | Specific gravity of anchor boulder | 2.65 |
| $V[m/s]$ | Mean flow velocity | variable |
| $\alpha$[deg] | Angle of rootward with respect to flow direction | 90 |
| $\beta$[deg] | Angle in horizontal plane | variable |
| $\Phi$[deg] | Friction angle of anchor boulder on streambed | 40 |

Table F.1: All parameters used in the equations

# G | LWD Jam stages from Manners



**Treatment:** Wrap natural jam with plastic wrap keeping as much of the natural shape as possible.
**Jam Structure:** Single, non-porous object
**Goal:** 1) Simulate non-porous object
2) Represent hypothetical end member in evolution of a jam
**Application:** Jams 2 and 3

**Treatment** None
**Jam Structure:** LWD and MWD racked onto the key member(s), SWD, soil and leaf litter occupy spaces among LWD and MWD
**Goal:** 1) Assess those jams formed completely by natural processes
2) Determine the natural porosity of jams
**Application:** Jams 1, 2 and 3

**Treatment:** Remove SWD, soil, leaf litter and any large unstable pieces
**Jam Structre:** Key member(s) with a LWD and MWD framework
**Goal:** 1) Assess the role of the small debris and organic matter in both jam structure and local hydraulics
2) Assess the role of a largely porous jam through a framework of LWD and MWD
**Application:** Jams 1 and 2

**Treatment** Remove remaining accumulated woody debris.
**Jam Structure:** Key member(s)
**Goal:** 1) Assess the hydraulic influence of the key member(s)
2) Determine the role of all accumulated material
**Application:** Jams 1, 2 and 3

Figure G.1: Stages of LWD jams

# H | Bennett ELJ flume experiments

Contour plots of normalised time-averaged parameters. The reference condition map (left) shows the flow field without any structures present. The additional maps show ELJ-1 (middle) and ELJ-2 (right) for the upstream (top) and downstream (bottom) cross sections. Red lines indicate in flow widths of the ELJs.

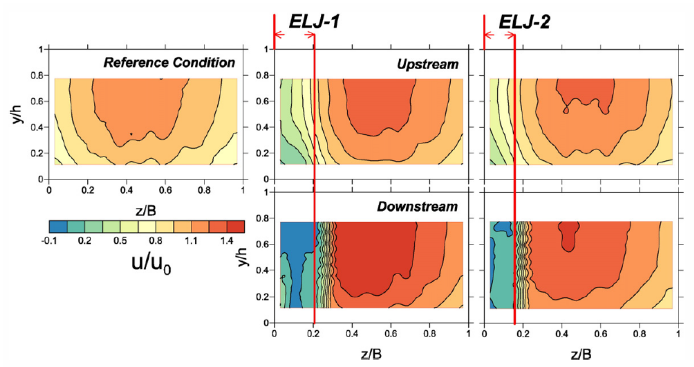


Figure H.1: Contour plots of the averaged flow velocities.

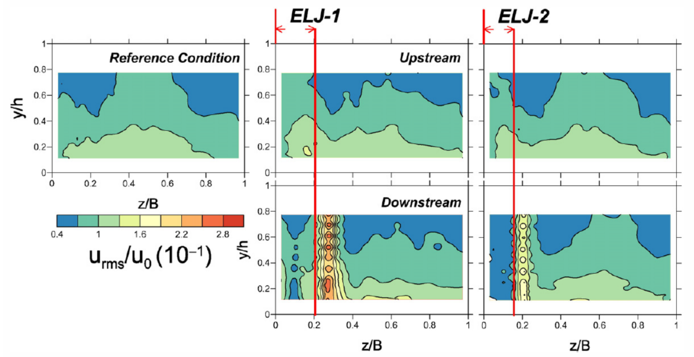


Figure H.2: Contour plots of the flow velocities in the direction of flow.

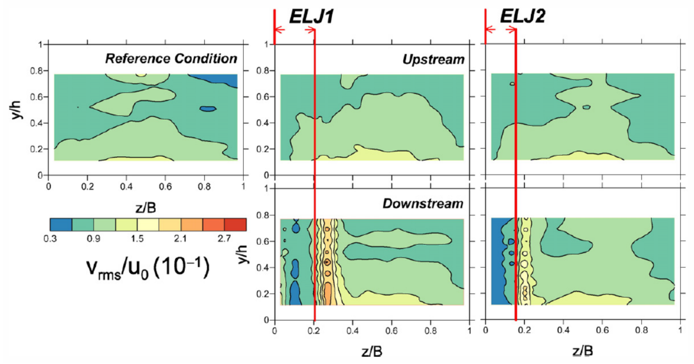


Figure H.3: Contour plots of the flow velocities perpendicular to the direction of flow.

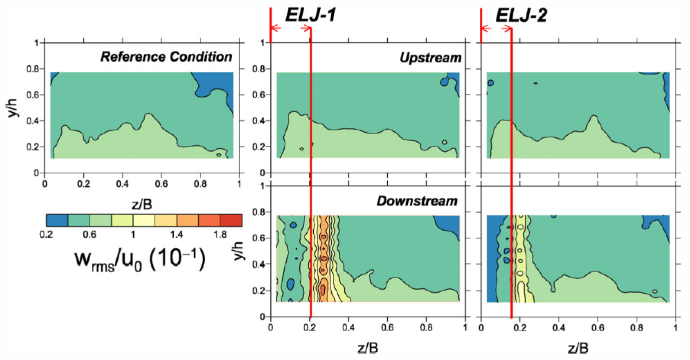


Figure H.4: Contour plots of the vertical flow velocities.

Contour plots of normalised downstream parameter in the near-flow field region. Reference condition (top), upstream and downstream of ELJs (columns 1 to 4) and for a single structure (first row) and two structures differently spaced (rows 2 to 4). Spacing is defined as a multiple of the water depth (h).

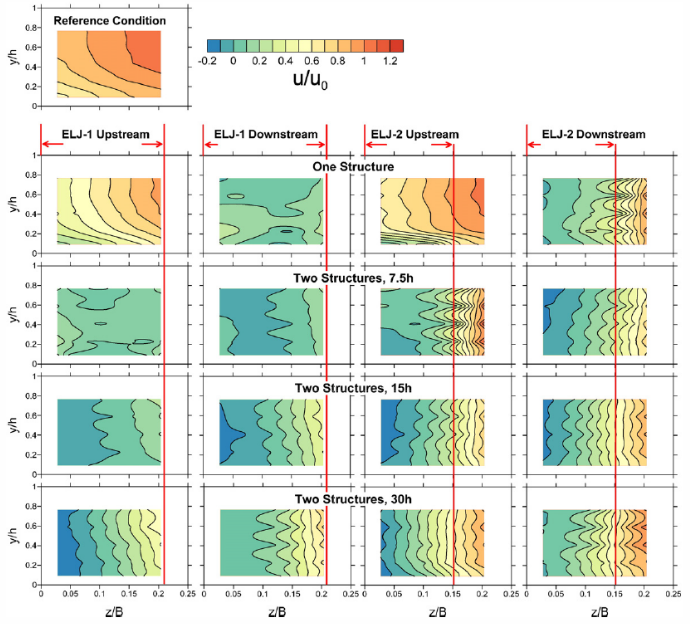


Figure H.5: Contour plots of the flow velocities.

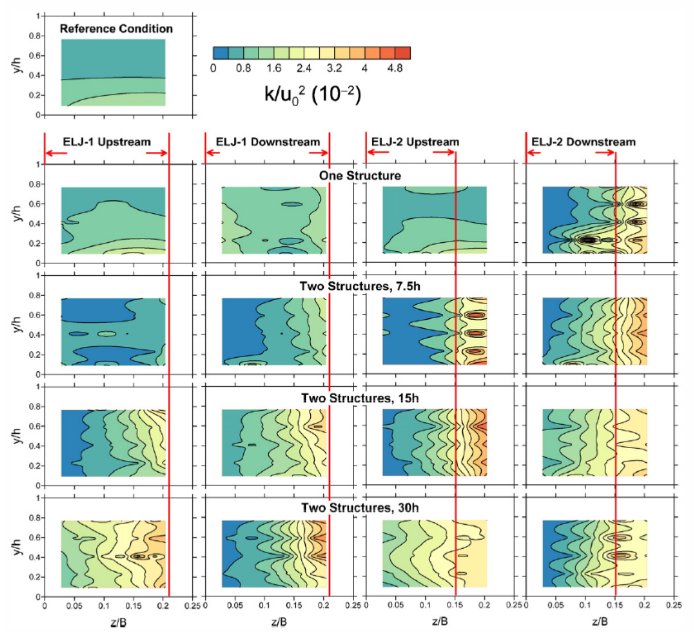


Figure H.6: Contour plots of the turbulent kinetic energy.

# I | Results Svoboda

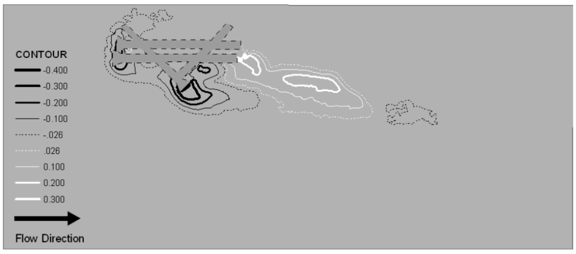


Figure I.1: Configuration 1: Triangular structure contour map

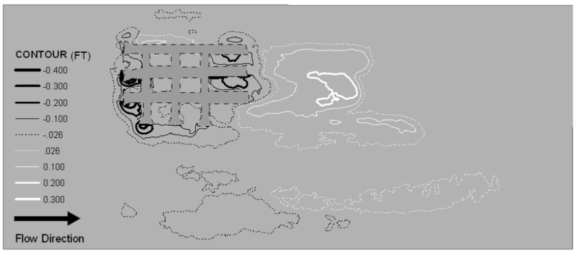


Figure I.2: Configuration 2: Rectangular structure contour map

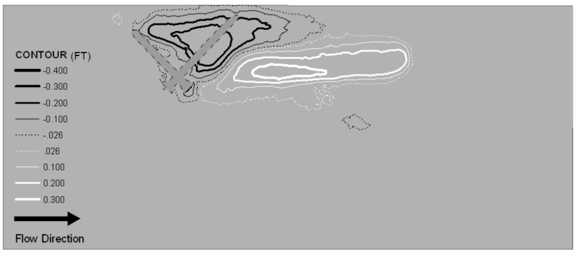


Figure I.3: Configuration 3: Cross-structure (downstream) contour map

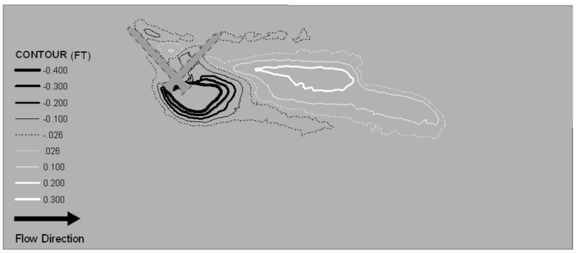


Figure I.4: Configuration 4: Cross-structure (upstream) contour map

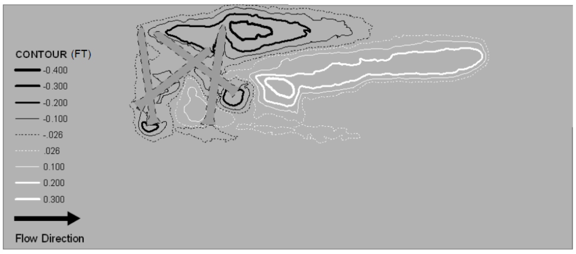


Figure I.5: Configuration 5: Free-form structure contour map

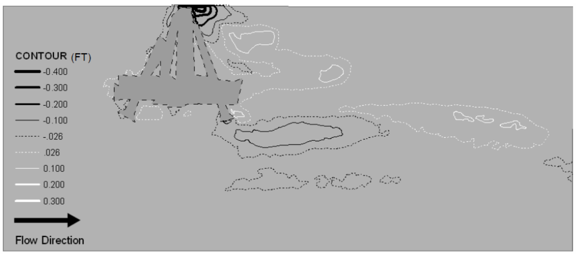


Figure I.6: Configuration 6: Bar Apex Jam contour map

# J | ELJ types by Abbe et al.

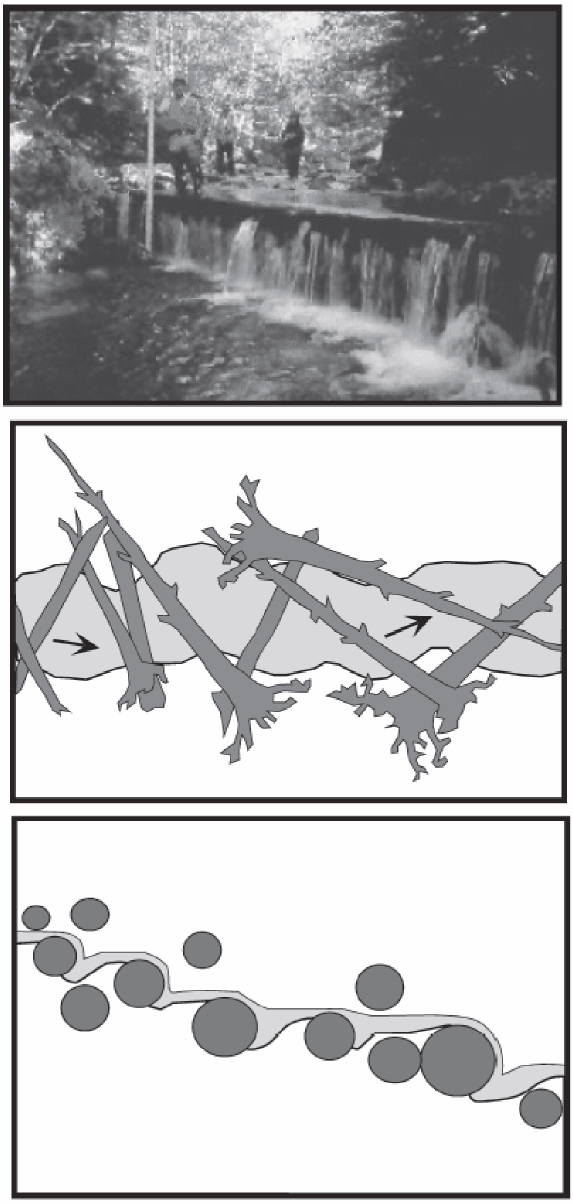


Figure J.1: Multi-log weirs, found in small streams. Comparable with Dam and Underflow jams, 2.7.

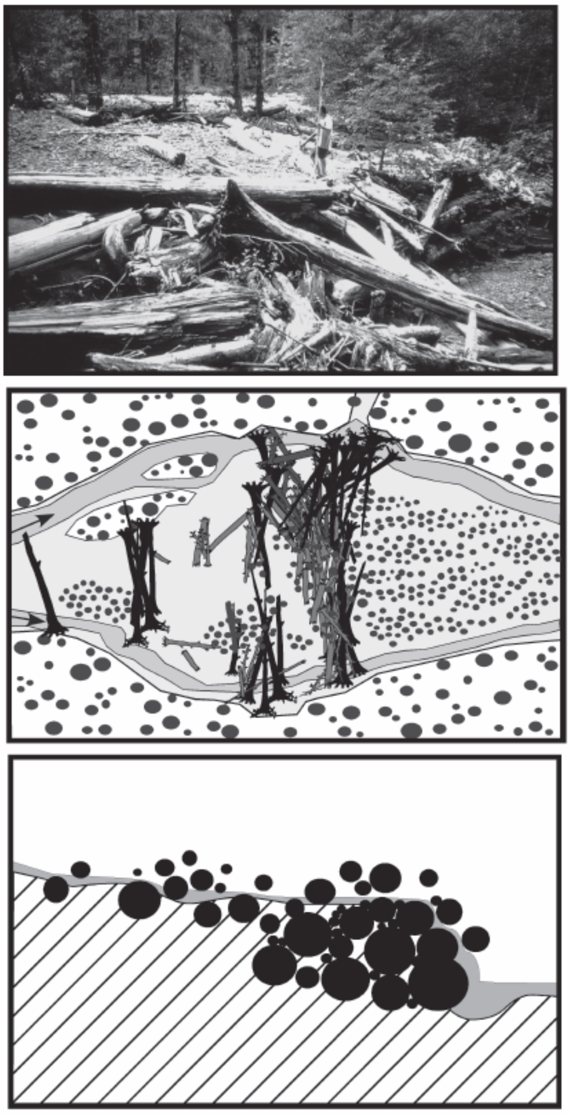


Figure J.2: Very large Step jams. Can raise the bed level over 5m. Create complex channel networks across the valley where they occur.

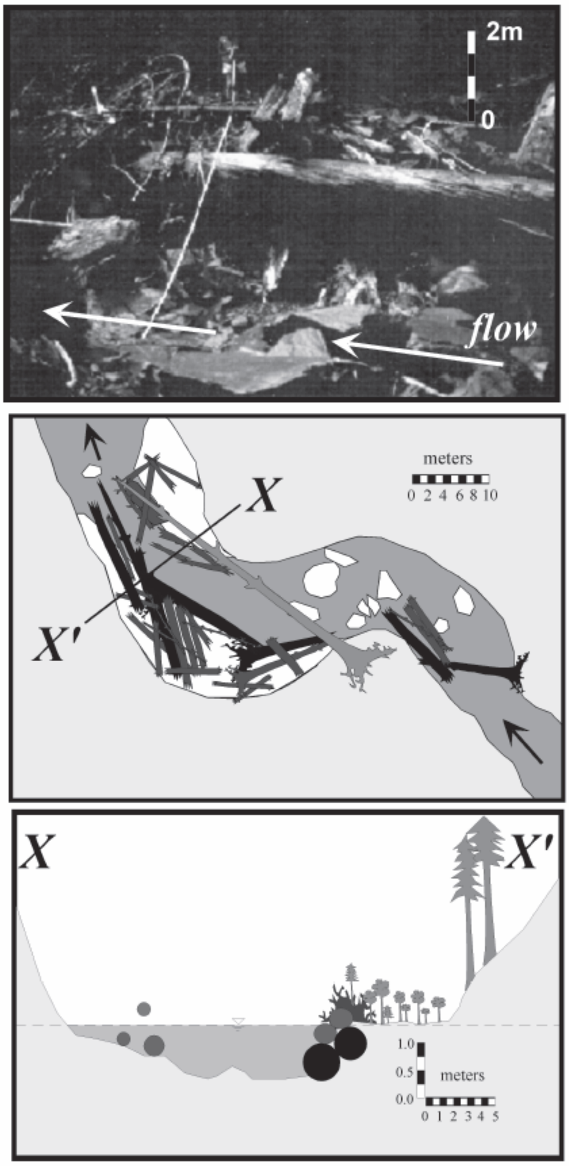


Figure J.3: Found in small, steep channels. Wedged logs create local floodplains and riparian vegetation and can also act as bank protection.

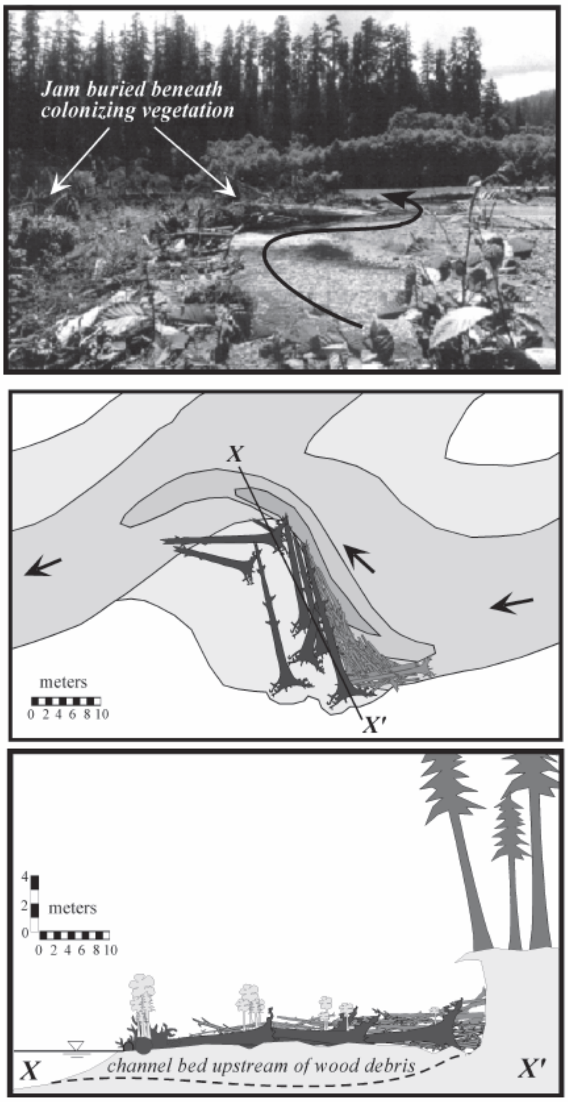


Figure J.4: Start out as one key member by falling trees. Accumulate debris over time and are eventually integrated in the stream bank, as opposed to flow diversion ELJs

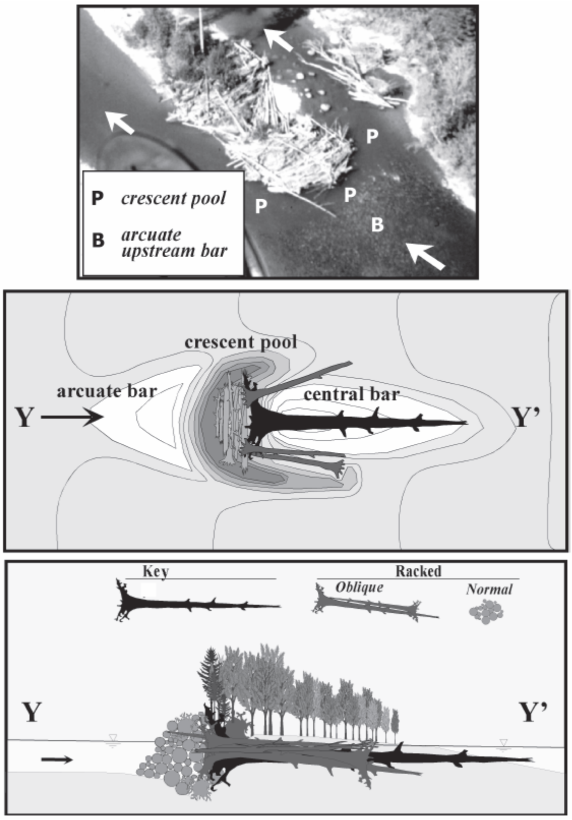


Figure J.5: Bi-directional flow diversion structures found in low gradient streams. Creation of bars up- and downstream allow for colonisation of vegetation.

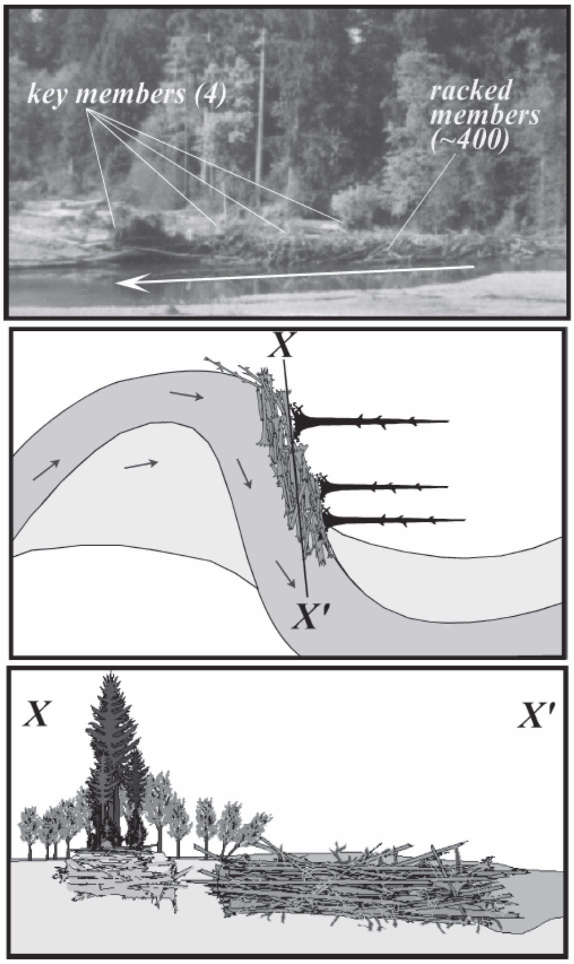


Figure J.6: Large flow diversion structures found in large meandering streams. Limit channel migration, protect banks and restore aquatic and riparian habitat