Lowland River Systems - Processes, Form and Function

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Giant ice sheets and melt water have formed the landscape and river valleys.
1 Lowland river systems – processes, form and function

Present day river valleys and rivers are not as dynamic and variable as they used to be. We will here describe the development and characteristics of rivers and their valleys and explain the background to the physical changes in river networks and channel forms from spring to the sea. We seek to answer two fundamental questions: How has anthropogenic disturbance of rivers changed the fundamental form and physical processes in river valleys? Can we use our understanding of fluvial patterns to restore the dynamic nature of channelised rivers and drained floodplains in river valleys?

Danish rivers, their floodplains and river valleys – formation and characteristics

During the last Ice Age the forces of flowing water and erosion by glaciers created the river valleys. The Danish islands and eastern and northern parts of Jutland were covered by a gigantic ice cap during this Ice Age. Underneath the ice, water was flowing in melt water rivers from the base of the ice cap to the glacier fronts. Melt water flowed in the valleys of the glaciated landscape, thereby enhancing the landscape features (i.e. hills and valleys) already present. On its way to the glacier front, the fast-flowing melt water eroded deep valleys, while the slower-flowing waters deposited sand, gravel and stones as ridges (hills). The outcome can be seen in the Danish landscape today, for example in the deep valleys of eastern Jutland where the River Gudenå and its tributaries flow. In addition, the melting of large ice blocks, left in the valley following the retreat of the ice cap, created lakes such as those in the River Gudenå valley.

At the glacier front in mid-Jutland, the melt water concentrated in several large rivers that flooded the moraine landscape in western parts of Jutland. The glacial melt water created large washout plains where sand, gravel and stones were deposited. Today these washout plains are heath plains acting as wide river valleys between the old moraine hills. The heath plains are river valleys for some of the large contemporary rivers in Denmark. The river with the greatest discharge in Denmark, the River Skjern, runs west from Nørre-Snede between Skovbjerg and Varde moraine hills and enters the sea in a large delta in Ringkøbing Fjord.

Since the last Ice Age rivers and streams have eroded the pristine moraine landscape and have formed floodplains and valleys along the rivers and streams (Figure 1.1). On the moraine hills exposed during the last Ice Age in western Jutland, the streams have had approximately 100,000 years to interact with the surrounding landscape. This long period explains why
the valleys and floodplains are wider in western Jutland than in the relatively young moraine landscape of eastern Denmark.

In northern Jutland the post-glacial rise in sea level (Yoldia Sea) created marine deposits near the shores. These have subsequently been exposed by the tectonic upheaval of the landmass. They form the present-day wide river valleys, bordered by former sea cliffs that now stand out as steep eroded hillsides, in this part of the country. A good example of this is the Skals Stream, north of Viborg. As a consequence of postglacial landmass movement, land subsidence in the southern part of Jutland has created special conditions where the present-day rivers are flowing in marine deposits and continuously adjust their morphology to the rising sea level. On the island of Bornholm, the presence of bedrock creates an in-stream environment different from anywhere else in Denmark.

**The river valley – intimate interactions between river and floodplain**

Rivers are naturally in a dynamic equilibrium with their valley and floodplain. The stream slope and flowing water create the energy needed for transporting eroded soil particles from stream banks and hillsides in the catchment to the sea. Erosion is most prevalent in the upper river system, where many small streams are in close contact with the surrounding landscape. Groundwater and drainage water from the catchment also supply vast quantities of dissolved substances to the streams. These are also subsequently transported to the sea.

In the lower part of natural, unmodified river systems, flooding of the river valley occurs regularly at high-flow events. During flooding vast quantities of sediment and organic debris are deposited on the floodplain. Close to the stream bank most of the sand is deposited as levees. Finer sediment and organic particles are deposited further away from the stream. The flooding waters, sediment and organic material are an important renewing source of nutrients to the floodplain. In natural systems these supplies of nutrients and sediment are essential for the growth and development of natural floodplain vegetation. In this way nature has created a buffer...
system delaying the loss of nutrients and sediment to the sea and enhancing the recycling of nutrients within the catchment. A substantial proportion of the suspended material being carried by floodwaters can be deposited on the floodplain and hence retained within the catchment (Figure 1.2).

Streams in undisturbed lowland landscapes will naturally wind or meander through the river valley. A stream moves from side to side within the river valley by eroding sediment on the outside of meanders and depositing the sediment on the inside of meanders further downstream. It is a slow physical process, which evolves over decades or centuries. In some cases the stream erodes at the base of the valley sides, thereby slowly widening the floodplain. The constant lateral movement of rivers and streams occasionally leaves meanders cut off and isolated on the floodplain as small oxbow lakes. Vegetation and deposited material from the stream will eventually fill the lakes and create small wetlands on the floodplain. Oxbow lakes have a characteristic mixed vegetation assemblage, different from that on the rest of the floodplain, and are quite distinct features in our natural river valleys.

The structure and composition of floodplain soils are highly variable. The Brede Stream valley in southern Jutland has alternating layers of sandy stream deposits, peat and organic material on its valley floor (Figure 1.3). Deposits of organic origin generally dominate soils in Danish river valleys. Decomposed coarse plant material makes up peat layers and fine particulate organic matter and diatom shells deposited in shallow waters make up the gyttja layers.

Figure 1.2 Floodplain sediment deposition during high flow events can reduce the sediment transport to the sea. During two 9-day flooding events in the lower part of the Gjern Stream (catchment area: 110 km²) between 6% and 11% of the transported sediment was retained on the floodplain [1].

Figure 1.3 The diversity of soil types in the river valley of the Brede Stream is considerable. The channel of this 4-km reach was re-meandered in 1994 in an initiative by the County of Southern Jutland. The river valley was drained and the river was channelised in 1954. Oxidation of the organic soil layer has caused a 0.5 m subsidence of the floodplain over the period of 40 years [2].
In total, 6,700 km² (15%) of Denmark’s area consist of such poorly drained soils rich in organic layers. These soils are primarily found in the river valleys and on raised seabed deposits in northern Jutland and in the salt marsh areas in southern Jutland. These soils have been in high demand because when drained they provide excellent nutrient-rich soils for agriculture.

Streams – a network of unidirectional flow
River systems form a finely branched network of many small, headwater streams that meet to form fewer and larger streams that finally merge into one large river reaching the sea (Box 1.1). From upstream brooks to the downstream river, water is continuously received from the surrounding land. The influence of the catchment landscape on stream morphology depends on soil type, topography, terrestrial vegetation and land use. Streams therefore form a unique ecosystem because of the linear connections within the network, the unidirectional flow and the intimate contact with the land.

Many brooks are formed by springs located near the base of steep slopes, where water leaves the groundwater reservoir. The confluence of several springs forms a spring brook, which is characterised by stable discharge and water temperature. Further downstream the confluence of spring brooks forms a stream, usually 0.5–2 m wide. Streams increase in size as they flow downstream becoming larger, 2–4 m wide. Even further downstream at the confluence of the larger streams, the river is formed.

During high flow events the natural unregulated watercourse floods the river valley and sediment and nutrients are deposited on the flood plain.
There is never a long distance to the sea from anywhere in Denmark. Rivers, in the strictest sense, are therefore not very common. Denmark has only two large rivers: the River Gudenå, which is the longest river and the River Skjern, which has the highest discharge (Box 1.2).

**Flow and substrata from spring to river**

With increasing distance from the spring, the stream usually becomes wider, deeper and transports more water (Figure 1.4 and 1.5). Large rivers often originate in mountains, run down the mountain slopes and across plains towards the sea. Along the course, the slope decreases [4]. This is generally also the case in the short river systems in Denmark, where the steepest slopes are usually found in the springs and brooks, and the lowest slopes in the rivers close to the outlet [5, 6]. However, on the local scale Danish streams follow a more irregular course with shifting reaches of steep or low slopes. This is primarily due to the presence of lakes, which act as hydraulic thresholds and re-set the natural dynamics of the flowing streams. Because of the local irregularities reaches with steep slopes and high physical stress may occur anywhere along the course.

Gravity, acting on the slope of the water surface, drives the downstream flow. The mean current velocity along reaches also depends on the resistance to flow exerted by the streambed, banks and plant surfaces. Since upstream brooks are shallow and narrow, water flows in intimate contact with the streambed and banks. So in spite of a steeper slope, the mean current velocity is usually lower in small Danish brooks than in large rivers [3, 4].
Local flow conditions above the streambed regulate erosion and sedimentation of particles. Although we may intuitively assume that steep headwaters have coarse gravel and stone substrata while large rivers have fine-grained sand and mud, this does not apply to Danish lowland streams – neither in their original unregulated state nor in their contemporary regulated state. In a nationwide study of 60,000 plots (25 × 25 cm) in 350 reaches across 75 streams, we did not observe systematic changes in the main substrata along the stream courses. Sand was the most common bottom substratum in both small and large streams (approx. 40% of all plots). In streams less than 2 m wide, gravel and stones were found in 30% of the plots, while 23% of the plots in streams more than 8 m wide had sediments dominated by gravel and stones. Mud was also frequent in small (32%) and large streams (23%).

**Box 1.3 Lowland channel patterns**

Classification of channel patterns in lowland streams. The channel pattern is the result of many processes interacting at many scales, and a classification scheme provides an overall insight into the dominant processes and parameters (modified from [5]).

Stream slope, water discharge, sediment supply and grain size distribution of transported sediment, control the channel planform pattern in rivers and streams. Since these parameters change systematically through the river channel system, the same would be expected from the channel planform pattern. In the following section we examine how the link between channel form and physical processes generates the distinct channel patterns.

Stream channel patterns have traditionally been classified as straight, sinuous or meandering [3, 7, 8] (Box 1.3). The straight and sinuous channels are generally found in the upper parts of the lowland river systems where the channel slope is high and discharge is low. These streams are often found in the moraine landscape and the stream bed substratum is dominated...
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Equally by sand and gravel/stones with scattered fine sediments. Erosion dominates in this part of the river system and material is continuously added to the stream from bank erosion and overland flow. The combination of sandy moraines and addition of material ensures also a continuously high proportion of sand on the stream bed. Stream power is insufficient to remove the coarse material, and the stones and gravel are left in channel, whereas clay, silt and fine sand are transported further downstream as suspended solids in the water. Within the streams, sidebars of coarse material are formed, with areas of fine-grained sediment deposited in between. In streams with very steep slopes the streamed bed is made up of a series of steps dominated by gravel and stones and finer sediments in pools between the steps. As discharge increases, stream power also increases despite the lower slope, and the stream can transport a wider range of sediment sizes, resulting in significant sediment transport along the streambed. This in turn leads to the development of riffles and pools characteristic of the sinuous channel. Further downstream, with greater stream power, the characteristic lowland meandering channel is formed. In natural sinuous and meandering streams erosional zones occur at regular intervals. Along the outside of the meander bends sediment is eroded and deposition occurs further downstream on the inside of meanders. Various sediment sizes can be transported, depending on the strength of stream power. Fine sediments such as clay, silt and fine sand are transported in the water column as suspended solids, whereas coarse sand and gravel are transported along the stream bed. Coarse sediment is concentrated in the riffles, where flow divergence cause stream power to decrease locally, leaving the flow incapable of moving coarse particles such as gravel and stones. Fine sediment can be captured between the large particles forming a very compact riffle structure typically found in lowland streams [8]. The fine sediment is deposited on the inside of meanders where current velocity decreases – the depositional areas on the inside of meanders are known as point bars.

**The cross section**

Channel pattern and cross sectional profile change as you travel down through the river system. With increasing distance from the source, depth, width and current velocity vary as a function of discharge (Box 1.4). These relationships are known as the hydraulic geometry of the stream and vary depending on geological and geomorphological conditions in the catchment and variations in climatic conditions [1]. Since geology affects the ability of the soil to be eroded, and climate and groundwater conditions affect the amount of water drained through the channel, the hydraulic geometry relationships can be expected to vary significantly among streams in different parts of Denmark.

On the sandy washout plains of western Jutland, streams receive a large proportion of groundwater all year round. These streams tend to be deeper and less varied in their depth than...
Box 1.4  Hydraulic geometry

Systematic variations in the physical properties of the channel and flow through the river system can be described using a set of equations, known as the hydraulic geometry relationships [3].

\[ w = aQ^b \quad \text{d} = cQ^f \quad U = kQ^m \]

Where: \( w \) is the bankfull width, \( d \) is the bankfull depth and \( U \) is the mean current velocity at bankfull discharge, \( Q \) is the bankfull discharge, \( A \) is catchment area, \( a, c, k \) are constants and \( b, f, m \) are exponents. Note that for any given relationship \( b + f + m = 1 \) and \( a \times c \times k = 1 \).

The relationships are indicated as log-log plots of the dependent variable width, depth or mean current velocity as a function of the discharge (or catchment area). The constants and exponents reflect properties of the catchment from where the stream water is drained. Different river systems in different parts of the world will thus have different constants and exponents reflecting differences in climate, geology and geomorphology.

<table>
<thead>
<tr>
<th>Exponents</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>( f )</td>
</tr>
<tr>
<td>Upland river (Appalachians, USA)</td>
<td>0.55</td>
</tr>
<tr>
<td>Great-plains river (Mid-western USA)</td>
<td>0.50</td>
</tr>
<tr>
<td>Lowland river Denmark (River Skjern)</td>
<td>0.48</td>
</tr>
</tbody>
</table>

In-stream habitats – predictable and variable

Running water actively forms the physical habitats within streams. We have already shown how substratum composition varies through the river system from source to sea. Now we take a closer look at the variations at a finer scale, within a given stretch of stream.

In all lowland stream types, from straight to meandering, the stream habitats alternate between sections of high and low current velocity. In areas of high current velocity, coarse sediment dominates, whereas fine sediment dominates in areas of low current velocity. The longitudinal distance between successive areas of high current velocity is approximately 5–7 times the width of the stream.

The ultimate development of this habitat variation is the riffle and pool sequence, which is a dominant feature of all meandering streams (Box 1.5). Riffles and pools are distinctly different habitats with respect to substratum, depth and current velocity (Figure 1.7). These fundamental physical differences are also reflected in the species composition and abundance of macroinvertebrate communities in the two habitats [12].

At an even finer scale, there are significant variations in substratum, depth and current velocity within the distinct habitats and the varied nature of small-scale habitat features underlines the heterogeneous nature of lowland stream (Box 1.6). However, local habitat structure within any stream reach still depends in part on large-scale conditions such as flow regime, and local conditions such as river valley slope, meandering and riparian vegetation structure. Variations in these controlling factors potentially influence the
habitat structure between any riffle in a
stream and cause significant differences in
the micro-habitat structure both
within and among riffles. These small-
scale differences in habitats clearly
affect the composition and abundance
of the local biotic communities [13].

At first glance lowland streams are
physically homogenous with consistent
and predictable variations in their
physical features from source to sea.
Local hydrological, geological and
landscape conditions influence the general
pattern of channel sinuosity. At the
channel reach-scale, riffles and pools alternate, creating different environments. Within these distinct habitats there is considerable fine-scale variability in habitat conditions. And yet despite this small-scale heterogeneity, we are capable of predicting general patterns in habitat structure and biotic communities throughout the river system from source to sea.

**Box 1.5 Channel morphology**

Current velocity, depth and streambed substratum vary in a predictable manner in natural stream channels. The distance between two neighbouring riffles in a meandering channel is 5–7 times the channel width. Straight channels exhibit identical alternating patterns.

The channel sinuosity is defined as the length between two points along the deepest part of the channel (known as the thalweg) divided by the distance along a straight line between the points. Natural straight or sinuous channels in the upper parts of the river systems have sinuosities between 1.05 and 1.5 and naturally meandering channels have sinuosities higher than 1.5. The sinuosity of the streams in Denmark has been used to quantify the total length of natural channels in all river systems [11]. The total estimated length of channels in Denmark was found to be approximately 2,000 km. Almost half of these natural streams are found in the western and southern part of Denmark.

**Figure 1.7** Substratum, depth and current velocity of riffles and pools in a lowland stream in Denmark. Pools are deeper areas in the streams with low current velocity and fine substratum. In contrast riffles are the fast velocity and shallow areas dominated by gravel substratum.
Variations in substratum, depth and current velocity in riffles are considerable in lowland streams when surveyed in detail, as here from the Tange Stream, Denmark. Small-scale variations are part of the dynamic environment that characterises in-stream habitats in streams around the world. Large-scale characteristics of the individual habitats (riffle/pool) usually hide considerable variations at smaller scales.

**Box 1.6 Small-scale variability in riffles**

Variations in substratum, depth and current velocity in riffles are considerable in lowland streams when surveyed in detail, as here from the Tange Stream, Denmark. Small-scale variations are part of the dynamic environment that characterises in-stream habitats in streams around the world. Large-scale characteristics of the individual habitats (riffle/pool) usually hide considerable variations at smaller scales.

**Human impacts on Danish rivers, floodplains and valleys**

River valleys and streams cut through the countryside as corridors connecting the land and sea by supplying a green vein for transport of water, sediment, nutrients, plants and animals. Streams, river valleys and floodplains have been extensively exploited since the first humans inhabited Denmark after the last Ice Age. In the beginning, river valleys acted as ideal places for settlements because of the possibility of combining fishing and hunting. Later, streams and rivers became valuable sources of energy for water mills. Dams that were constructed on many watercourses now obstruct the free flow of water from source to sea. Larger streams and rivers were important means of transport, e.g. barge transport from Silkeborg to Randers on the River Gudenå during the 18th and 19th century, and are still widely used for recreational canoeing today. Fish farms were established in many river valleys during the 20th century and they used the stream as a source of water for breeding and rearing trout.

However agriculture has caused the most radical changes to the rivers and floodplains. For centuries floodplains were used for cattle and horse grazing and also for haymaking, used for winter fodder. Over the past 100 years...
agricultural practices have intensified, primarily due to increased crop production. This has resulted in drainage and construction of ditches in river valleys and the straightening and channelisation of many streams, to increase drainage efficiency. Advanced technology increased the development of drainage schemes, in particular by means of tile drainage throughout eastern parts of Denmark. Many small streams in the upper river systems were culverted in order to ease the use of agricultural machinery. Physical changes to the river valleys have altered hydrological conditions and affected both vegetation and animals. As a consequence of the drainage schemes carried out during the last century, Denmark has now almost no pristine streams and river valleys. Channelisation and straightening have physically modified more than 90% of the stream network of 64,000 km (Box 1.7).

The extensive floodplain drainage has caused significant subsidence of river valleys soils. This phenomenon is caused by decomposition of the peat layers when exposed to atmospheric oxygen. Subsidence levels of 0.5 m are very common in many river valleys and levels of up to 1 m have been measured in the lower part of the River Skjern system, even though this area was drained as late as the 1960s [15]. As a consequence of the subsidence, the beds of ditches and streams have had to be further lowered and tile drainage has been renewed.

Large-scale channelisation and straightening of streams has increased sediment erosion and mobilisation. In order to maintain drainage capacity in channelised streams, excess sediment had to be removed from the streambed, causing continuous disturbance to stream conditions. This maintenance is currently still required in many streams. The recurring need for removal of sediment from the streambed has profound consequences for stream flora and fauna. Streams have gradually become wider and deeper than they would have been under natural conditions. At the same time straightening of the streams has reduced the stream length, which leads to an increase in stream bed slope. In order to compensate for the increased slope weirs were constructed in the streams, whereby most of the energy was concentrated in a few large weirs. These weirs have acted as obstructions to the free movement of animals and

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**Box 1.7 Habitats in channelised and restored reaches**

In channelised rivers and streams uniform cross sections with steep banks have replaced the natural irregular cross sections. The uniform physical conditions have reduced in-stream habitat diversity in many Danish streams. The dredging activities have removed coarse substratum (gravel and stones) from the stream and fish spawning grounds have been lost. The combination of these actions has reduced the available habitats for macroinvertebrates and fish.

The habitats are more varied in a restored reach of the Gelså Stream compared to an upstream channelised reach [14].
plants. Over 140 such obstructions were found within a restricted area such as Sønderjylland County (3,940 km²) in the late 1980s.

The repeated disturbances caused by dredging helps to increase sediment transport both in terms of suspended transport and transport along the streambed. Over a period of 3 months following maintenance work on the Gelså Stream, sediment transport increased by 370 tonnes of which 280 tonnes was registered as bed-transported material [16]. An increase of this magnitude can have devastating effects on the stream biota due to sand intrusion into salmonid spawning grounds and general habitat degradation for macroinvertebrates.

What initiatives are needed to reverse the physical degradation of rivers and floodplains?

Public interest in restoring the natural dynamics of streams and floodplains has been growing over the past 15 years. The best example of a completed project is the restoration of meanders along the River Skjern and the re-establishment of wetlands on its floodplain. Prior to these initiatives, vast sums of money had been invested in improving water quality in Danish rivers and streams. As water quality has improved it has become increasingly clear that it is now primarily the physical degradation of the rivers and floodplains that limits biological diversity.

Over the last 20 years hundreds of projects have focused on removal of obstructions in streams. These projects have enhanced the opportunities for salmonoid fish to reach their upstream spawning areas. Unfortunately, these efforts have not been supported by restoration of spawning grounds that were lost during the period of continuous dredging of stream sediments. The effective lack of restoration of spawning grounds is made very difficult by the defeatist attitude towards the excess continuous transport of sand into the streams, which causes rapid siltation of the gravel beds. It is obviously necessary to track down, identify and combat the excess sediment delivery and thereby reduce the sediment transport. Actions could encompass a more effective enforcement of the existing compulsory 2 m-wide uncultivated buffer strips along streams or the establishment of wider buffer strips, with no agricultural production, to prevent sediment reaching the channel.

The only possible way to re-establish more natural physical and biological conditions in the thousands of kilometres...
of streams is to change maintenance procedures, including timing, frequency and intensity of dredging and weed cutting. Future maintenance must include gentle procedures in those parts of the river systems where the potential for the development of diverse floral and faunal communities exists. Over the past 20 years maintenance procedures in many streams administered by municipalities and counties, have been changed towards gentle and selective weed cutting that leaves some vegetation in the channel and on the banks, and dredging activities have been reduced. Documentation detailing the procedures that have the most positive effect on biodiversity is, however, still lacking. There is an urgent need for experimental studies in different Danish stream types to determine which maintenance procedures are most successful at sustaining and improving stream biodiversity.

In order to proceed from here, a holistic approach to river and floodplain restoration is required. We need to see the river valley, the floodplain and the stream as one unit in a landscape mosaic. Information on the physical diversity of the river valley and its streams therefore needs to be integrated in a system allowing classification of rivers and river valleys according to geomorphology, hydrology and geological setting. The ultimate goal of our restoration efforts should be based on physical and biological data on the structure of the few remaining undisturbed streams in Denmark.

The river and river valley classification systems in combination with the established biological reference conditions of our streams in different parts of the country will be an important tool for future decisions on how and where to implement restoration schemes. We also need to gather both short-term and long-term information on how the river and floodplain ecosystems respond to the restoration. The future success of our restoration effort will rest on our ability to document ecosystem responses to past restoration efforts and subsequently to improve our methods based on this knowledge.