Modelling downstream change in river flood power and bank erosion: a novel approach combining flood flow assessment with Digital Elevation Models of stream slope

Modélisation des changements en aval de la puissance des crues fluviales et de l'érosion des berges : une nouvelle approche combinant l'évaluation du débit des crues avec les modèles numériques d'élévation de la pente du cours d'eau

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RÉSUMÉ

La puissance des cours d'eau est un facteur important dans les processus fluviaux, notamment : l'instabilité du lit des cours d'eau, le taux et le processus d'érosion des berges et le transport des sédiments. Cependant, on sait peu de choses sur la structure spatiale de la distribution de l'énergie des crues à l'échelle du bassin entier. Nous développons ici une nouvelle approche intégrée permettant de quantifier la distribution en aval à l'échelle du bassin de la puissance brute de l'inondation, Ωf, et de la relier à la dynamique des rivières. Les points forts particuliers de la méthodologie sont que les approches d'estimation des crues (FEH) génèrent ici des amplitudes de débit massives en de nombreux points en aval des réseaux de drainage conventionnels dans plusieurs bassins fluviaux. Les valeurs de débit sont calculées et combinées avec les valeurs de pente des DEM à l'échelle des bassins versants pour produire des séries de données de puissance de crue quasi-continues le long des principaux cours d'eau du bassin. Les résultats pour les grandes rivières du Royaume-Uni montrent que les valeurs de puissance des cours d'eau changent en aval de manière complexe ou non linéaire, et peuvent souvent atteindre leur maximum au milieu du bassin. Les résultats fournissent un support solide pour les simulations. Les taux d'érosion des berges sont en rapport avec la puissance aux cours d'eau à l'échelle des bassins. Les résultats ont des implications importantes pour l'explication et la gestion des processus fluviaux. De telles approches peuvent être développées pour d'autres contextes fluviaux à l'échelle internationale.

ABSTRACT

Stream power is a strong control of fluvial processes, including: river channel instability; bank erosion rates and processes; and sediment transport. However, little is known about spatial structure of flood power distributions at full basin scales. Here, we develop a novel, integrated approach to quantify basin-scale downstream distributions of gross Flood Power, Ωf, and link these to river dynamics. Particular strengths of the methodology are that Flood Estimation (FEH) approaches here generate bankfull flow magnitudes at numerous points downstream throughout mainstream drainage networks in several river basins. Flow values are computed and combined with slope values from DEMs at catchment scales to produce near-continuous flood power data series along entire river basin mainstems. Results for larger UK rivers show that stream power values change downstream in complex or non-linear ways, and can often peak in mid-basin. Findings provide strong support for simulations. Bank erosion rates link well to stream power at catchment scales. Results have important implications for the explanation and management of river processes. Such approaches can be developed for other fluvial contexts internationally.

KEYWORDS

Stream Power spatial variations, Downstream Change, Basin-scale Hydrodynamics, River Bank Erosion

1 INTRODUCTION

Stream power is a strong control of several fluvial and ecological processes, including: river channel instability and pattern; bank erosion rates and processes; bedrock channel incision; sediment transport; flood defence stability; water quality issues; and water aeration and habitat development.

However, little is known about the spatial structure of fluvial flood power distributions at the basin scale, because of outstanding problems of numerical simulation, data availability and measurement protocols. Therefore, it is presently very difficult to assess directly the full patterns and controls of downstream stream power distributions on fluvial processes, such as river bank erosion, channel change and hydroecology. It has also been uncertain how the spatially-variable catchment 'architectural properties' of river slope covary with flood discharges to produce given longitudinal stream power distributions.

2 METHODS

We address these important research gaps by developing a novel, integrated approach which quantifies basin-scale downstream distributions of gross Flood Power, Ωf, defined as ρgQSf, where ρ is fluid density, g is gravitational acceleration, Q is bankfull discharge and Sf is floodplain slope. We call this the CAFES methodology, i.e. the Combined Automated, Flood, Elevation and Stream power system.

Particular strengths of the novel methodology are that Flood Estimation (FEH) approaches here estimate bankfull flow magnitudes at numerous cross-sections in a downstream sequence throughout whole river basins. Bankfull discharges are calculated at very high spatial resolution: these are derived from numerous catchment and river system driving variables, including catchment slope and elevational-difference datasets, average annual precipitation, basin land use, and fluvial system properties, using CEH Flood Estimation algorithms.

The resultant bankfull discharge values are then combined with quasi-continuous river slope values extracted from Digital Elevation Models, again at catchment scales, to produce near-continuous flood power data series along entire river basin mainstems.

The novel approach thus elucidates the full spatial structure and downstream change in stream power and river flow energy at an unsurpassed spatial resolution. Stream power values here are calculated for the 2-year return period flood level – a highly significant event for erosion and sediment transport. To do this, the new approach couples (a) spatially-continuous bankfull flood discharge data from improved and automated UK Flood Estimation modelling approaches, with (b) floodplain slope values derived from catchment and reach Digital Elevation Models.

Resultant catchment-scale flood power distributions are tested against conceptual and numerical simulations. Stream Power values can be validated against field surveys and alternative flood discharge assessments.

3 RESULTS

Main results are presented here for the largest UK rivers in the UK (e.g. Severn, Thames; Severn; Trent; Feshie and Wharfe) representing upland, piedmont and lowland catchments and reaches, mainly in western and upland Britain.

First, absolute peak and mean power values tended to increase westwards from lowland basins towards upland Wales.

Second, within individual catchments, flood power distributions showed strong downstream change.

Third, and most interestingly, downstream flood power distributions often emerged as highly non-linear, with peak stream power in mid-basin. (e.g. Fig. 1). These new findings provide strong support for some previous theoretical simulations. Some catchments displayed multiple stream power peaks which challenge existing power models.

Fourth, at reach scales, tributary junctions were also important components in the catchment power architecture, and were sometimes characterised by significant, but transient subsidiary stream power peaks.

Finally, we show how bank erosion rates in the River Severn – one of the largest rivers in the UK - are linked to stream power distributions in interesting ways – stream power distributions which still reflect historic events.

4 CONCLUSIONS

These results, based on novel combinations of catchment- and reach- scale analytical approaches, have important implications for the understanding, explanation, prediction and management of stream power. The findings elucidate spatial patterns of river system instability at catchment and national scales, and help to identify bank erosion, sediment and pollutant transport continuity at basin scales; longitudinal distribution of fluvial processes and process-zone coupling, with potential to define development, and operation of freshwater habitats. There is substantial potential to expand these analytical approaches to other fluvial contexts for wider international application.

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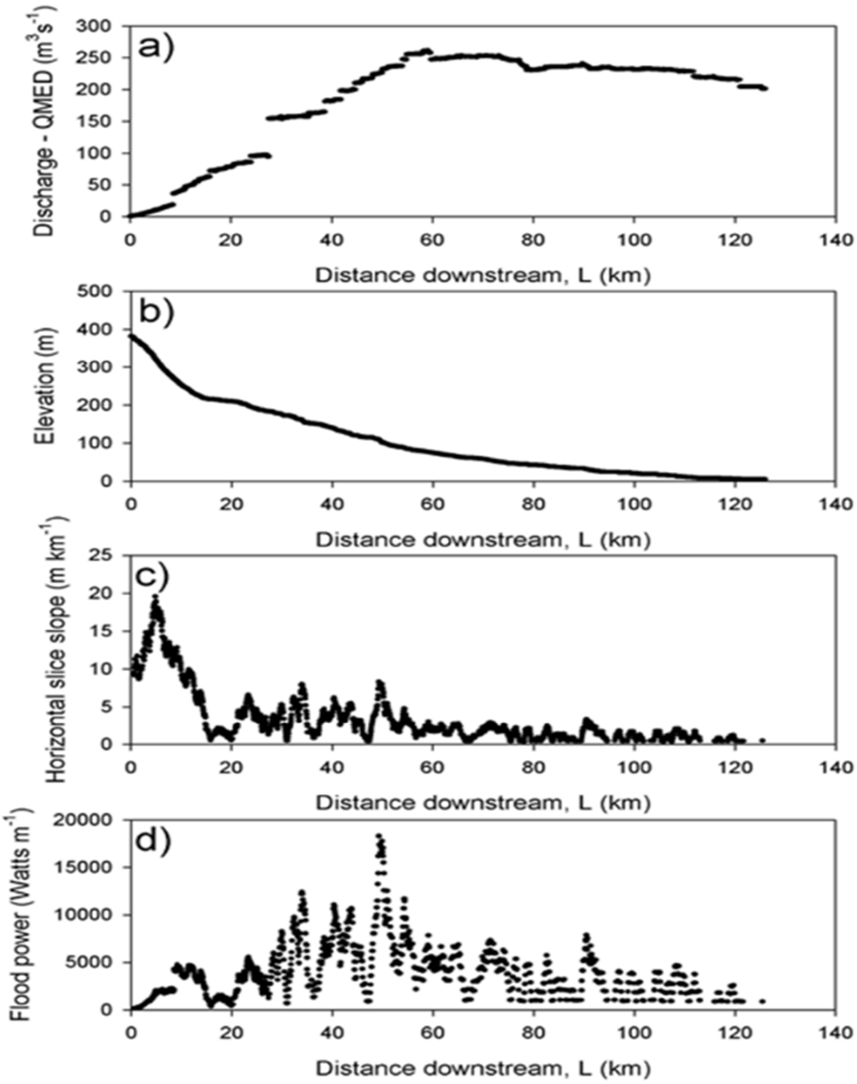

Fig 1. Example of the River Wharfe, UK: Downstream stream power and channel hydraulics changes. Note mid-basin stream power peak (Fig 1d).