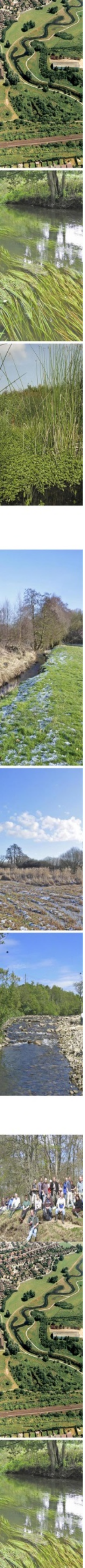


River Restoration and 2D modelling Science Digest

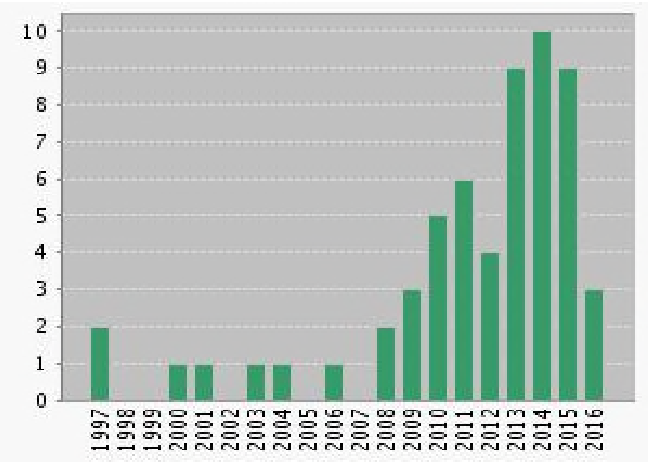
Aim

The following science digest on river restoration and 2D modelling is aimed at providing practitioners with a short summary of the most recent scientific papers and case study examples of the applications of 2D hydrodynamic models to river restoration schemes. Each article is briefly summarised and the major findings or points of methodology are described. Articles are grouped into relevant themes and they are ordered according to relevance. A summary of the literature is provided at the beginning of the Science Digest. Readers are invited to comment on papers and add case studies and published literature to the digest. This can be done in the comment section or by joining the Mendeley River Restoration and 2D hydraulic model group. The group is open to all and members will be able to share publication details and text. Mendeley is a free referencing software used by researchers across the world and owned by the publisher Elsevier.

Summary

Background

A search on Scopus and the Web of Science using the following keywords “2D AND River Restoration” yielded 58 publications from 1997 to 2016 (see graph below). The number of publications on the subject has increased since 2008 and peaked in 2014. A selection of relevant publications are listed and summarised in the present digest.



Publications could be split into four broad themes of application (the number of publications in each theme are in brackets):

- Modelling and sampling frameworks (5),
- Best practice river restoration techniques (12) ,
- Habitat suitability assessment (13), and
- Floodplain restoration appraisal (4).

Hydrodynamic modelling

Before getting into more detail, it is important to understand what modelling is all about. A hydrodynamic model attempts to model flow depth and velocities across a river channel using computer algorithms based on physical equations describing flow dynamics. The key data requirements for modelling are:

- A detailed map of the channel bed and the floodplain topography;
- An assessment of the bed, banks and floodplain roughness (as indicated by vegetation, substrate etc.);
- Water depths and velocity profiles for different discharges for calibration.
- Additional depth and velocity data for validating (i.e. testing) the model.
- Records of past rainfall, discharge and flooding may also be collated for calibrating and testing the model further.

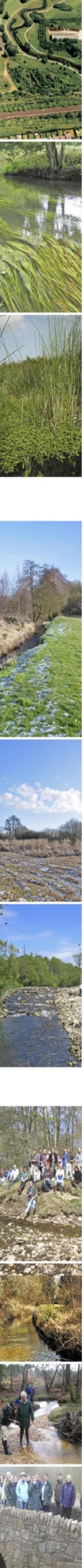
Topographic data for the floodplain can be collected using aerial or Lidar surveys whereas channel data generally requires field surveys. Depending on the type of models used, survey intensity varies. One-dimensional (1D) models are run using cross-sectional survey data collected at regular intervals along the river (e.g. 100m) whereas two-dimensional (2D) models require bed topography to be recorded on a grid along and across the channel. For 2D models, the sampling intensity depends on the nature of the application and it may be necessary to sample every square-meter.

One-D and 2D models differ not only in the amount of data they require but also in the algorithm they use, the time to produce the models and the nature of the outputs. With 1D models, flow is modelled along the river whereas 2D models model velocities along and across the channel. This means that 2D models are potentially more suited to modelling overbank flows across the floodplain as well as complex flow patterns around in-channel structures. Both modelling systems produce maps of water depth and velocities for given discharges.

Theme summaries

The **modelling and sampling frameworks** section contains a series of publications laying the methodological foundation for applying 2D models to river restoration. Wright et al (2016) highlight the need for a comprehensive approach towards model building, including model calibration and validation on a separate dataset. They also emphasise the need to collect ground data at the scale of the processes of interest. This was originally discussed by Crowder and Diplas (2000) who showed the importance and impact of including small features such as boulders in the topographic survey when modelling microhabitats. Errors in topographic measurements can lead to significant errors in model prediction as demonstrated by Pasternack et al (2006). Two-D models, however, are not always necessary. Gibson et al (2015) discuss and compare 1D versus 2D models for mapping habitat suitability whereas Hughes et al (2016) illustrate how simplified versions of 2D models can be applied to aerial data for broad scale assessments.

In the **best practice river restoration techniques section**, models are specifically applied to river restoration design issues. The RRC 2005 report on rehabilitation guidance provides a very useful overview of the potential use of modelling techniques for river restoration with an assessment of costs, benefits and data requirements. Models have been applied to a series of design issues, mainly riffle-pool rehabilitation/creation, erosion and deposition.



Brown et al (2016) and Schwartz et al (2015) demonstrate how 2D models can be used to design and deliver process-based riffle-pool restoration. They used 2D models to design a self-maintaining pool-riffle sequence based on the flow convergence and shear stress reversal hypotheses. Models were also used to assess erosion and deposition patterns in channel and on the floodplain following restoration (Lai et al 2015, Neary et al 2013, Biron et al 2009) and for predicting maintenance (i.e. dredging) requirements (Van Vuren et al, 2014).

The **Habitat Suitability Assessment** section lists a whole suite of article and research where 2D models have been applied towards mapping habitats for fish species. Wheaton et al (2004) suggested a framework for carrying out such assessment combining model predictions for depth and velocity with surveyed attributes (e.g. channel substrate) and simple Habitat Suitability Curves (HSC) relating fish density to predicted and measured attributes. This approach has been applied to a range of rivers and habitats for assessing the impact of river restoration options (see the ‘option appraisal’ section) and some level of correlation was observed between predicted habitat and fish occurrence following tests (Gard, 2006 and Boavida et al 2013). Although a lot of effort was put into modelling flow accurately, habitat suitability is generally assessed using fairly crude relationships mainly based on two attributes (flow and velocity) whose relationship to fish density is often simplified and variance is ignored (Wheaton et al 2004). Knapp and Preisler (1999) showed that salmon redd occurrence was not only related to depth and velocity but also to channel substrate size, location and bank vegetation cover. The combination of all these attributes explained 62% of red occurrence suggesting that a substantial amount of variability was controlled by other un-measured attributes. Boavida et al (2013) showed that variables other than velocity and depth (e.g. vegetation cover) explained fish occurrence.

Two-dimensional models were also applied to designing and **appraising floodplain restoration** schemes. Clilverd et al (2016) successfully modelled surface and grounwater levels following embankment removal on a chalk stream. Leyer et al (2012) showed how a 2D model could be used for reinstating floodplain forest whilst minimising flood risk. Hughes (2000) and Poulsen et al (2014) used modelling to assess erosion and deposition patterns and Wen et al (2013) for appraising floodplain management options.

The ‘**case studies**’ section contains a list of applications of 2D models to river restoration in the ‘grey’ literature. Available case studies were mainly related to option appraisal of river restoration schemes with regards to flood risk. It potentially reflects the needs and requirements of government organisations to improve habitats whilst minimising impacts on local communities and businesses.

Scientific publications

Modelling and sampling frameworks

Modelling frameworks

Wright, K.A., Goodman, D.H., Som, N.A., Alvarez, J., Martin, A., Hardy, T.B., 2016. Improving Hydrodynamic Modelling: an Analytical Framework for Assessment of Two-Dimensional Hydrodynamic Models. River Res. Appl. http://doi.org/10.1002/rra.3067

The authors propose a framework for building, calibrating and validating 2D models. Models are often not tested against data collected separately. The authors suggest collecting data for flow events not used in calibration so that the models can be assessed for their ability to predict flow depth, velocity, inundation extent and water surface elevation. They highlight the importance of surveying topography at a scale relevant to the processes of interest. For example, microhabitat modelling applications for predicting juvenile and adult salmon may require dense topographic data (e.g. 0.4 points per m^2).

Kail, J., Guse, B., Radinger, J., Schröder, M., Kiesel, J., Kleinhans, M., Schuurman, F., Fohrer, N., Hering, D., Wolter, C., 2015. A modelling framework to assess the effect of pressures on river abiotic habitat conditions and biota. PLoS One 10. http://doi.org/10.1371/journal.pone.0130228

The authors describe and apply a complex modelling framework where 1D and 2D models are combined with morphological and biological models to assess the impact of pressures such as discharge changes, water quality, land use, riparian vegetation, channelization and barriers to migration at catchment and reach scales.

Crowder, D.W., Diplas, P., 2000. Using two-dimensional hydrodynamic models at scales of ecological importance. J. Hydrol. 230, 172–191. http://doi.org/10.1016/S0022-1694(00)00177-3

The authors show the importance of including features potentially impacting flow such as boulders when modelling streams for ecologically-driven river restoration schemes. Using a 2D model of a stream, they demonstrate the potential impact of boulders on flow depending on their location in the channel.

Pasternack, G.B., Gilbert, A.T., Wheaton, J.M., Buckland, E.M., 2006. Error propagation for velocity and shear stress prediction using 2D models for environmental management. J. Hydrol. 328, 227–241. http://doi.org/10.1016/j.jhydrol.2005.12.003

In this study, the authors tested 2D model predictions on a river restoration scheme against measured depth, velocity and shear velocity. The errors were, respectively, 21%, 29% and 31%. Depth error was mainly due to topographic survey errors, which in turn explained more than half of flow and shear velocity prediction error. In spite of these limitations, shear stress estimations were not significantly different from observed values and predicted habitat feature distribution at the 3-100m (i.e. meso to macro habitat) scale was comparable to predicted outputs. (See also: Pasternack et al 2004)

1D versus 2D

Gibson, S.A., Pasternack, G.B., 2015. Selecting Between One-Dimensional and Two-Dimensional Hydrodynamic Models for Ecohydraulic Analysis. River Res. Appl. 1365–1381. http://doi.org/10.1002/rra.2972

Comparison of 1D and 2D hydrodynamic models for assessing depth and velocities in channels with a literature review and cost-benefits analysis. 1D models performed well compared to 2D for predicting depths with R^2 about values greater than 0.94. The models did not perform as well on velocities with R^2 values between 0.42 and 0.81 and larger residuals. Large velocity residuals were associated with backwaters and areas downstream of islands, boulders or outcrops. The authors suggest that 1D models require more experienced modellers and are therefore prone to higher levels of variability.

Note: the 1D model seemed to over predict velocities near the bank and at meander bends, which could be problematic for river restoration. From a cost-benefit viewpoint, the study was performed on sites with complete bathymetry. Complete bathymetry is required for 2D models and is expensive to collect. It is not clear how comparable the 1D model outputs would have been in the absence of complete bathymetry so the practical cost-benefit of using 1D versus 2D could not really be properly assessed.

Pseudo 2D models

Hugue, F., Lapointe, M., Eaton, B.C., Lepoutre, A., 2016. Satellite-based remote sensing of running water habitats at large riverscape scales: Tools to analyze habitat heterogeneity for river ecosystem management. Geomorphology 253, 353–369. http://doi.org/10.1016/j.geomorph.2015.10.025

Use of a pseudo 2D model in combination with satellite imagery to model habitat distribution and heterogeneity over a large river. Satellite pictures were used to derive water depth based on spectral band ratio. Flow velocities were estimated using depth and discharge values (predicted). River reaches were identified using cluster analysis on depth, velocity and width. The method is only applicable to fairly wide non turbid stream with limited canopy cover.

Best practice river restoration techniques

Model use and limitations

RRC, 2005 River rehabilitation guidance for eastern England rivers, RRC, 92pp

This manual provides guidance on when and how to use various modelling techniques for river restoration. The benefits, limitations and risk of using flow modelling techniques are assessed for specific river restoration practices such as channel narrowing, riffle introduction and gravel bed raising, backwaters, meander reconnection etc. The flow modelling techniques assessed are: 1D and 2D models, modelling using the Conveyance Estimation System (CES) or hand calculations. For each method, costs, data requirements and expertise needed are indicated. Illustrated case study examples are provided for each river restoration technique.

Process based river restoration design

Riffle-pool

Brown, R.A., Pasternack, G.B., Lin, T., 2016. The Topographic Design of River Channels for Form-Process Linkages 57, 929–942. http://doi.org/10.1007/s00267-015-0648-0

Pool and riffle design options are investigated using a 2D model. The authors consider options based on changes of width and depth for creating self-sustaining pool-riffle sequences. According to theory, pool-riffle sequences need to display flow convergence at riffles and flow divergence at pools and higher levels of shear stress in pools at high flow. The design options for pool-riffle restoration were: local channel widening, river bed augmentation (e.g. rock-riffles introduction), channel fluctuation in width and depth (e.g. narrow shallow 'step' riffle with wide and deep pool), and out-of-phase fluctuation in width and depth (i.e. wide shallow riffles and deep narrow pools). The results show that widening or augmenting streams alone is not enough to reinstate processes that will maintain pool-riffle structure. Only wide shallow riffles over narrow and deep pools fulfil the requirement of the flow convergence and shear stress reversal hypotheses.

Schwartz, J.S., Neff, K.J., Dworak, F.E., Woockman, R.R., 2015. Restoring riffle-pool structure in an incised, straightened urban stream channel using an ecohydraulic modeling approach. Ecol. Eng. 78, 112–126. http://doi.org/10.1016/j.ecoleng.2014.06.002

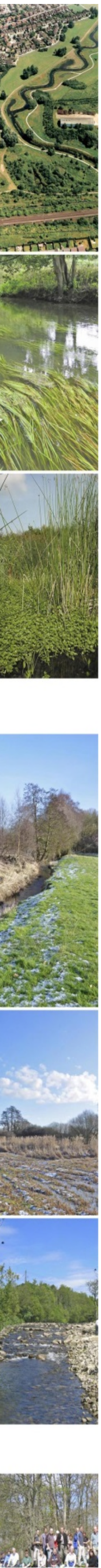
Methods for designing riffle pool sequences in straightened river reaches using a 2D model. The 2D model was used to assess the impact of trees growing on the bankface on the development of helical flows conducive to riffle development and maintenance. The analysis led to the removal of trees and widening of the channel where riffles were introduced. The model was also used to assess bank stability and introduce reinforcements where appropriate. Finally, the model was used to map available habitats for three fish species after rehabilitation.

Brown, R.A., Pasternack, G.B., 2009. Comparison of methods for analysing salmon habitat rehabilitation designs for regulated rivers. River Res. Appl. 25, 745–772. http://doi.org/10.1002/rra.1189

Comparison of 1D and 2D numerical models for riffle pool design. The results show the limitations of 1D analytical methods for assessing riffle pool hydraulics, sediment transport and physical habitat quality.

Pasternack, G.B., Bounrisavong, M.K., Parikh, K.K., 2008. Backwater control on riffle-pool hydraulics, fish habitat quality, and sediment transport regime in gravel-bed rivers. J. Hydrol. 357, 125–139. http://doi.org/10.1016/j.jhydrol.2008.05.014

Use of a 2D model to study the impact of backwater effects on riffle pool formation and habitat quality for salmon.



Erosion and deposition

Van Vuren, S., Paarlberg, A., Havinga, H., 2014. The aftermath of "Room for the River" and restoration works: Coping with excessive maintenance dredging. J. Hydro-Environment Res. 9, 172–186. http://doi.org/10.1016/j.jher.2015.02.001

Use of a 2D model to assess the impact of restoration options on sediment transport, accumulation and maintenance (dredging).

Lai, Y.G., Thomas, R.E., Ozeren, Y., Simon, A., Greimann, B.P., Wu, K., 2015. Modeling of multilayer cohesive bank erosion with a coupled bank stability and mobile-bed model. Geomorphology 243, 116–129. http://doi.org/10.1016/j.geomorph.2014.07.017

In this paper, the authors implement a 2D model to successfully predict bank erosion on a river bend.

Lai, Y.G., Greimann, B.P., 2010. Predicting contraction scour with a two-dimensional depth-averaged model. J. Hydraul. Res. 48, 383–387. http://doi.org/10.1080/00221686.2010.481846

A 2D model was successfully used to predict river bed scour in a flume experiment. The results were comparable to a 3D model output.

Biron, P.M., Carré, D.M., Gaskin, S.J., 2009. Hydraulics of stream deflectors used in fish-habitat restoration schemes. WIT Trans. Ecol. Environ. 124, 305–314. http://doi.org/10.2495/RM090281

This study uses a 3D model to assess the impact of flow deflectors on areas of erosion and deposition. It highlights the limitations of 2D models in quantifying river restoration effects on habitat distribution.

Neary, V., Member, A., Wright, S., Bereciartua, P., 2013 sediment transport and 2D modes. J. Hydraul. Eng. 127, 901–910.

A 1D model with a high density DEM was used to assess erosion and deposition in three separate areas of a restored tidal river reach (channel, marshplain and floodplain). Model predictions were consistent to observed patterns and showed the potential for using this technique for erosion and deposition modelling.

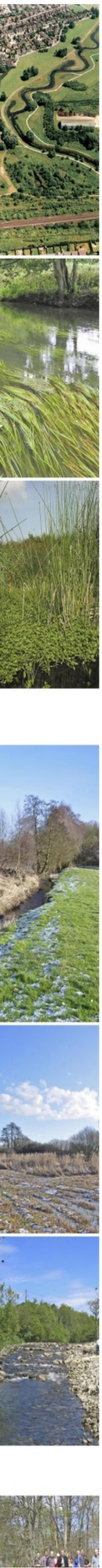
Bollaert, E., Duval, J., Maumary, L., Andre, S., Hohl, P., 2014. Restoration of the Broye delta into the Lake of Morat (Salavaux, Switzerland). CRC Press/Balkema, pp. 165–172.

Use of a 2D hydraulic model for the restoration of the Broye Delta in Switzerland.

Habitat Suitability assessment

Habitat suitability modelling framework and methods

Wheaton, J.M., Pasternack, G.B., Merz, J.E., 2004. Spawning habitat rehabilitation – I. Conceptual approach and methods. Int. J. River Basin Manag. 2, 3–20.



A methodological paper on the use of modelling for habitat rehabilitation. The authors suggest the use of 2D models to produce maps of depth and velocity that can be turned into habitat suitability maps for scenario testing. Habitat suitability is calculated using Habitat Suitability Curves (HSC) that relate species density to depth and velocity. The authors highlight some important limitations of the approach, particularly the fact that HSC curves are based on averaged values for depth and velocity around observed habitats, and that habitat suitability maps do not account for other habitat attributes such as the presence of nearby refuge and resting areas.

Wheaton, J.M., Pasternack, G.B., Merz, J.E., 2004. Spawning habitat rehabilitation – II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A. Int. J. River Basin Manag. 2, 21–37.

The method advocated by Wheaton et al (2004) was applied to a case study site. The authors advocate ‘transparent hypothesis development and testing’ during the design stage for testing options. Two-D models, Habitat Suitability Curves and indices are an important part of their framework.

Jung, S.H., Choi, S.U., 2015. Prediction of composite suitability index for physical habitat simulations using the ANFIS method. Appl. Soft Comput. J. 34, 502–512. http://doi.org/10.1016/j.asoc.2015.05.028

Use of a 2D model combined with the ANFIS method for computing habitat suitability for fish for restoration schemes. The ANFIS represents an alternative to Habitat Suitability Curves (HSC) and combine fuzzy logic models and neural networks. The methods compared favourably to the HSC approach.

Bandrowski, D.J., Lai, Y.G., Bradley, D.N., Murauskas, J., Gaeuman, D., 2014. 2D hydrodynamic based logic modelling tool for river restoration decision analysis: A quantitative approach to project prioritization, in: Proceedings - 7th International Congress on Environmental Modelling and Software: Bold Visions for Environmental Modeling, iEMSs 2014. International Environmental Modelling and Software Society, pp. 2092–2100.

Application of 2D hydrodynamic based logic model (2D-HBLM) to a 14 mile segment of the Trinity River (US) to prioritise projects with regards to their impacts on fish habitats. The complex modelling system combines a 2D hydraulic model with a habitat model to produce a series of metrics: biological, ecological, physical and constraints. The metrics are then analysed using a statistical tool called ‘Logic Model’ that prioritises the best restoration projects.

Fukuda, S., Tanakura, T., Hiramatsu, K., Harada, M., 2015. Assessment of spatial habitat heterogeneity by coupling data-driven habitat suitability models with a 2D hydrodynamic model in small-scale streams. Ecol. Inform. 29, 147–155. http://doi.org/10.1016/j.ecoinf.2014.10.003

Use of a 2D model with Habitat Suitability models based on depth and velocity to map habitats for a fish species in 2 agricultural canals. The habitat suitability models were derived using different modelling techniques: Artificial neural Network, Classification and Regression Tree, Random Forest and Support Vector Machines. The Random Forest yielded the best models in spite of low level relationships between fish density, depth and velocity.

Model validation and uncertainty assessment

Boavida, I., Santos, J.M., Katopodis, C., Ferreira, M.T., Pinheiro, A., 2013. Uncertainty in predicting the fish-response to two-dimensional habitat modelling using field data. River Res. Appl. 29, 1164–1174. http://doi.org/10.1002/rra.2603

In this study, the authors test a habitat suitability assessment using Habitat Suitability Curves and a 2D model against fish survey data for 2 species and 2 life stages (juveniles and adults). They find that areas with high habitat suitability were more likely to be populated by fish than areas with low suitability.

Pasternack, G.B., Wang, C.L., Merz, J.E., 2004. Application of a 2D hydrodynamic model to design of reach-scale spawning gravel replenishment on the Mokelumne River, California. River Res. Appl. 20, 205–225. http://doi.org/10.1002/rra.748

In this study, the authors used a 2D model to predict the impact of different layouts for gravel augmentation in a depleted reach (because of a dam) on habitat suitability for salmon (assessed using velocity and depth). The model predictions for depth and velocity were comparable to observed outcomes although velocities tended to be underestimated. An interesting insight is provided on the practical limitations of 2D models. The authors found that the model did not perform well over created bars and riffles because of the quality of the Digital Elevation Model (DEM). Topographic survey data resolution was high (cf 1 point per $3.6m^2$) but the DEM software used did not generate a topography that truly represented the terrain. Even with an accurate DEM, the authors found that the model did not perform well around Large Wood Debris (LWD) and failed to predict accurately habitat quality estimates and location as well as potential for sediment entrainment.

Gard, M., Fish, U.S., Service, W., 2006. Modeling changes in salmon spawning and rearing habitat associated with river channel restoration. Int. J. River Basin Manag. 4, 201–211. http://doi.org/10.1080/15715124.2006.9635289

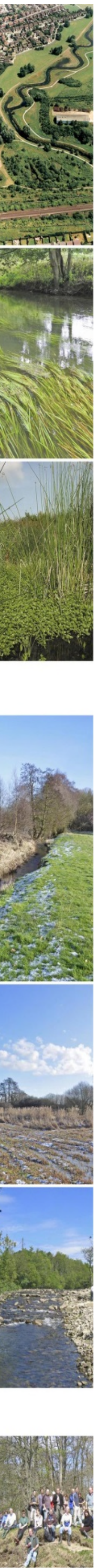
Use of a 2D model to assess the effectiveness of restoration on salmon habitat. The model outputs were compared before and after restoration using simulated data and real outputs (including biological data) and showed good performance for predicting spawning habitat but less so for rearing habitat.

Option appraisal

Boavida, I., Santos, J.M., Cortes, R., Pinheiro, A., Ferreira, M.T., 2011. Benchmarking river habitat improvment. River Res. Appl. http://doi.org/10.1002/rra.1561

Comparison of estimates of fish habitat extent for modified and reference sites using 2D hydraulic modelling. The model was used to test restoration options against reference condition.

Branco, P., Boavida, I., Santos, J.M., Pinheiro, A., Ferreira, M.T., 2013. Boulders as building blocks: Improving habitat and river connectivity for stream fish. Ecohydrology 6, 627–634. http://doi.org/10.1002/eco.1290



Use of 2D model for habitat suitability assessment for cyprinids using various boulder placements.

Lee, J.H., Kil, J.T., Jeong, S., 2010. Evaluation of physical fish habitat quality enhancement designs in urban streams using a 2D hydrodynamic model. Ecol. Eng. 36, 1251–1259. http://doi.org/10.1016/j.ecoleng.2010.05.004

Use of a 2D model for calculating usable areas for fish using different habitat improvement techniques: riffles, boulders and step-stones.

Lange, C., Schneider, M., Mutz, M., Haustein, M., Halle, M., Seidel, M., Sieker, H., Wolter, C., Hinkelmann, R., 2015. Model-based design for restoration of a small urban river. J. Hydro-environment Res. 9, 226–236. http://doi.org/10.1016/j.jher.2015.04.003

Use of a 2D model in a heavily modified urban river stretch to create habitat diversity for a series of fish species. The model was used in combination with habitat suitability indices based on depth and flow velocity to predict changes in usable areas for a series of river restoration design options.

Alfredsen, K., & Borsanyi, P. (2004). Application of habitat modelling in river rehabilitation and artificial habitat design. *Hydroécologie*, *14*, 105–117. http://doi.org/10.1051/hydro:2004007

Use of 2D hydraulic models with habitat preference curves to design a habitat enhancement scheme targeted at Atlantic salmon and trout. Not river restoration per se, but it demonstrates the potential use of modelling to assess critical habitat dimensions such as depth and velocity.

Floodplain restoration appraisal

Clilverd, H.M., Thompson, J.R., Heppell, C.M., Sayer, C.D., Axmacher, J.C., 2016. Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics. River Res. Appl. http://doi:10.1002/rra.3036

A 1D/2D model combination was used to model the impacts of removing embankments on a short section of a chalk stream in England. The model enabled the quantification of river-floodplain reconnection in terms of flooding extent and duration as well as impacts on groundwater levels during the year. Embankment removal reduced flood peaks by 6-24% and increased groundwater levels during dry period, favouring recolonisation by wetland species.

Leyer, I., Mosner, E., Lehmann, B., 2012. Managing floodplain-forest restoration in European river landscapes combining ecological and flood-protection issues. Ecol. Appl. 22, 240–249. http://doi.org/10.1890/11-0021.1

Example of the use of a 2D model to identify areas suitable for planting trees and reinstating floodplain forests. The model was used to delineate areas with suitable flow velocities and a planting strategy that would not increase flood risk.

Poulsen, J.B., Hansen, F., Ovesen, N.B., Larsen, S.E., Kronvang, B., 2014. Linking floodplain hydraulics and sedimentation patterns along a restored river channel: River Odense, Denmark. Ecol. Eng. 66, 120–128. http://doi.org/10.1016/j.ecoleng.2013.05.010

The aim of this study was to assess the impact of channel and floodplain restoration of a straightened river on overbank sedimentation using a 2D model. A regression model was built relating sediment deposition on the floodplain to predicted depth, velocity and distance to flow outlet ($R^2 = 0.76$).

Wen L., Ralph T., Hosking T., Barma D. and Saintilan N. , 2013 Assessing stream restoration works in the southern Macquarie Marshes using hydrodynamic modelling. 20th International Congress on Modelling and Simulation, Adelaide, Australia, 1–6 December 2013.

Use of a 2D model to predict the impact of channel restoration work on the flooding of wetlands and comparing management options.

Hughes, F.M.R., 2000. Floodplain biodiversity and restoration (FLOBAR): hydrological and geomorphological mechanisms influencing floodplain diversity and the application to the restoration of the European floodplains. In River Restoration in Europe, Practical Approaches. Nijland, H.J., Cals, M.J.R. ed. Conference on River Restoration, Wageningen, Netherlands.

Use of 2D modelling for predicting floodplain velocities and areas of erosion and deposition to inform restoration options. Application to the river Ouse.

Case studies

SEPA 2013 Physical restoration options to address morphology and flood pressures on the River Nith - a pilot study (October 2013)

A 'flow routing' 1D model of the River Nith channel coupled to a 2D model of its floodplain were developed for testing natural flood management options. The approach is less data intensive and does not require as much computational power and is therefore applicable to larger areas. A fully 2D hydrodynamic model can provide better prediction but requires more detailed bathymetric data and it is therefore more adapted to shorter sections of river.

Tweed Forum 2011 Eddleston water restoration

Use of a coupled 1D/2D model to assess options for floodplain restoration.

RIBBLE CATCHMENT CONSERVATION TRUST, 2012. Burnley options appraisal report final (v1.3). Report by JBA Consulting for the Ribble Catchment Conservation Trust.

Use of 1D-2D model to assess the impact of channel restoration options (riffle-pool) on flood risk in an urban system.

Other example available on http://tinyurl.com/z8chpk7

Cited publications (not reviewed)

Knapp, R. a., Preisler, H.K., 1999. Is it possible to predict habitat use by spawning salmonids? A test using California golden trout (*Oncorhynchus mykiss aguabonita*). Can. J. Fish. Aquat. Sci. 56, 1576–1584. http://doi.org/10.1139/cjfas-56-9-1576