Kneath, R. L., Williamson, S., & Nolden, C. (2023). *Evaluating the Environmental Impact of Micro Hydropower in Nepal*. Paper presented at 18th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia.

Peer reviewed version

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Evaluating the Environmental Impact of Micro Hydropower in Nepal

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ABSTRACT

In Nepal, Micro Hydropower Plants (MHP) are used to provide electricity to the local communities across Nepal typically using run-of-river dams which generate up to 100 kW of electricity. There is a current assumption that these MHP have a negligible environmental impact, which is partly due to the lack of literature researching this topic. Therefore, it is crucial to question this assumption, assessing the environmental impacts of MHP. This paper focuses on reviewing in-situ methods and remote methods for suitability for application in Nepal to determine if MHP have a negative environmental impact. Four case studies were carried out in the UK using RIVERCONN to evaluate its applicability in Nepal. RIVERCONN assesses the amount of river fragmentation within a basin using spatial data. It was determined that RIVERCONN was suitable as the data required is easily accessible and it provides an overview of the river connectivity at a basin scale where other methods are specific to individual MHP. This paper concludes future research should focus on implementing remote methods such as RIVERCONN and in-situ methods such as sampling and analysis to evaluate whether MHPs have an impact on the environment.

KEYWORDS

Micro-hydropower, Run-of-River, Nepal, Environmental Impacts, River Connectivity, RIVERCONN

INTRODUCTION

Hydropower is generated using the natural flow of a river. The water flows through turbines generating electricity which is either stored or transported to cities for use [1]. Across the planet, countries have been using hydropower since the first millennium BC [2], due to the many benefits. Depending on the type and size of the hydropower plant (HP) the benefits include electricity generation, irrigation, water supply and flood control [3,4].

There are three main types of HPs: impoundment plant, pumped-storage plant, and diversion plant. For the impoundment plant type, a dam is constructed to form a reservoir to control the flow of water. When electricity is required, the dam allows water to flow to the turbines, turning them, and generating electricity [1]. In recent years this form of hydropower has been found to have detrimental impacts on the environment [5]. The pumped-storage plant pumps water from a river at a lower elevation to a reservoir at a higher elevation at times of low electricity demand. When electricity is required, the water is released, flowing downhill through the turbines and into the river where it is pumped from [1]. Lastly, the diversion plant, also known as a run-of-river (ROR), does not use a reservoir but instead diverts a proportion of the river flow down a channel. The channel is connected to a powerhouse where the water is fed through a turbine generating electricity before returning to the river downstream [6]. For this paper, the focus will be on ROR hydropower plants.

There are different scales at which ROR HPs operate, ranging from large HPs operating on major rivers to pico HPs on streams. Table 1 shows the power generation for the different scales of ROR hydropower [7]. There is currently no uniform definition for each type of ROR HP, however, the one used in this paper was the most common in the literature [3,6,7,8,9].

Table 1. The several types of ROR HPs and electricity generation capacities [7]

ROR HP	Generation Capacity
Pico	< 10kW
Micro	10kW - 100 kW
Mini	100kW - 1MW
Small	1MW - 10MW
Large	> 10MW

This paper will focus on ROR HPs at the micro-scale, hereafter referred to as Micro HPs (MHP). Figure 1 shows the common layout of an MHP, where the process begins when water is taken from a river using an intake such as a weir. Once the water has travelled through the intake, it reaches the forebay where the water's speed is reduced to allow sediment to settle. The water then travels through the penstock to the powerhouse where the water travels through a turbine generating electricity, the water is then returned to the river. At the top of the penstock, there is a sluice gate which can stop the water flow for maintenance of the turbines. [6,10]. Due to the design of the MHP, differences in elevation are required between the intake and outflow. The elevation difference is referred to as 'head' with the intake being at a high head (high elevation) and the outflow being at a low head (low elevation). The change in head allows the water to flow from the river to the powerhouse without the use of pumps [3]. Another requirement of micro development is for rivers which have a constant flow of water all year round [3]. This means the location needs to be in a climate that provides a consistent supply of water to the river to allow electricity generation at a constant rate [6].

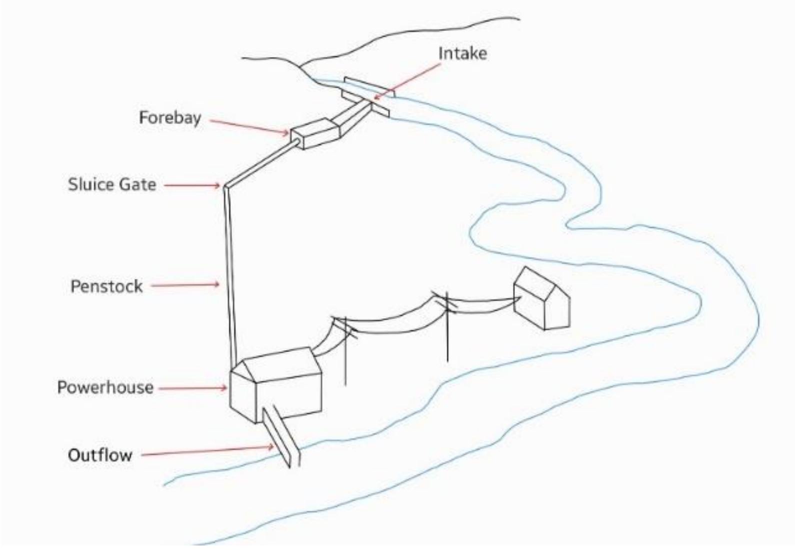


Figure 1. The common set-up of a Micro HP

A country like Nepal with its mountainous regions and constantly flowing rivers is optimal for micro hydropower development and as a result, Nepal has been using hydropower since the early 1900s. Approximately 3,300 off-grid MHP have been providing electricity to rural communities across Nepal since the 1960s [10]. Besides electricity generation, the MHPs have been providing clean drinking water and economic development [3,4,11]. It is commonly assumed that these MHP have negligible impact on the environment [3,6,8,11,12] with little research supporting this statement. Studies are being conducted to investigate the validity of the assumption. Many different methods have been used to evaluate the environmental impacts of hydropower across the world [5]. These different methods focus on a range of environmental changes and range from remote to in-situ methods. In this paper, these methods were evaluated to understand the data requirements, scalability, and sensitivity of each method. The purpose of this paper is to propose methods that could be applied in Nepal to ensure the operation of these MHPs are not causing environmental changes that will become irreversible. The paper is structured as follows. The next section introduces the methods and their suitability in two results sections. This is followed by the discussion and the conclusion.

LITERATURE REVIEW

Methods

A detailed literature review was conducted to understand the variety of methods used to assess the environmental impact of HPs. Google Scholar and Web of Science were used to find papers related to the study area by including the keywords; run-of-river, micro, small, hydropower and environmental impacts. As mentioned in the introduction, there is limited literature surrounding the environmental impacts of MHP. This resulted in using papers evaluating the environmental impacts of small HPs as the scalability of the method could be evaluated for application to MHP. Therefore, review papers were used to find methods that focused on the environmental impacts of micro and small ROR HPs [3,4,7,11,13]. From these review papers, the methodologies that appeared to be the most suitable were chosen for further research using the paper's references. The methods found were divided into three categories: time-series analysis, in-situ sampling and analysis and modelling impacts.

Time-Series Analysis methods use time-series data and analyse various aspects of the data to determine potential changes across the data. These methodologies focused on assessing the changes in the flow regime of the river by using data before and after the construction of the HP [14,15,16,17,18]. In-situ sampling and analysis focused on methods that used samples taken at the area of interest to analyse changes to a specific focus area due to the operation of a ROR HP. These types of methodologies focused on water quality and river geology [8,12,19,20,21,22,23,24]. Modelling Impacts included methods that used spatial data to assess environmental changes due to the operation of a ROR HP. These types of methodologies focused on assessing the connectivity of rivers at the basin scale [25,26,27,28,29,30,31]. All the methods that were found during the literature review for this paper have been included in Table 2. The table includes the name of the method, a brief description of the method, the data requirements, the benefits, limitations, and the literature that has applied the method.

Table 2. The Methods used to evaluate the environmental impacts of ROR HPs.

Method	Description	Data Requirements	Benefits	Limitations	Supporting Literature
Time Series Data Analysis					
Indicators of Hydrological Alteration (IHA)	A software that assesses the changes in flow regime by computing thirty-three hydrological parameters and 34 environmental flow parameters	Daily flow data. 20+ years of data	There is extensive literature applying the method in practice and therefore the results are dependable. The method can be applied remotely.	The data requirements can be difficult to fulfil in data-poor countries. Data gaps are estimated meaning reduced accuracy for incomplete data. Daily flow data may not pick up minimal changes to the flow regime caused by SHP and MHP	[14,15,16]
Instantaneous Streamflow Analysis Tool (INSTANT)	Written in the R programming language, this tool assesses the difference in flow data, quantifying changes in flow metrics caused by hydropower development and different operating scenarios.	Sub-daily flow data, up to 15-minute intervals. 5+ years of data	Using sub-daily data means the tool can identify slight changes in the river and potentially find changes caused by MHP. The results can be more accurate than IHA because sub-daily flow data is used rather than daily flow data. Requires less data compared to similar tools such as IHA. Allows the comparison of different operating scenarios to find the most environmentally friendly. The method can be applied remotely.	It can be difficult to find 5 years of sub-daily data in data-poor countries. There is a limited amount of literature that applies this method in practice and therefore the reliability is questionable	[17,16,18]
In-situ Sampling and Analysis					
Taking samples at one location over a period	Taking samples and testing them either in a lab or using onsite equipment to analyse a specific characteristic of the river at one specific location	Sampling equipment and analysis equipment that is specific to the focus area of the study.	Can detect changes that occur over an extended period. Able to focus on a specific characteristic of the river or a wide range of characteristics. The method can detect slight changes in the river because the focus area can be specified making it ideal for MHP	In developing countries, some MHP are in remote areas which can be difficult to access for sampling. It can be difficult to acquire the required equipment in developing countries	[12,19]
Taking samples at multiple locations once	Taking samples and testing them either in a lab or using onsite equipment at multiple locations on one occasion	Sampling equipment and analysis equipment that is specific to the focus area of the study.	Can analysis the environmental impact on the river at the basin scale by including multiple. Able to focus on a specific characteristic of the river or a wide range of characteristics. The method can detect slight changes in the river because the focus area can be specified	In developing countries, some MHP are in remote areas which can be difficult to access for sampling. It can be difficult to acquire the required equipment in developing countries. It can be difficult to acquire the required equipment in developing countries. The results may not be fully accurate as it does not take seasonality into account.	[20,21]
Taking samples at multiple locations over a period	Taking samples and testing them either in a lab or using onsite equipment at multiple locations over a period	Sampling equipment and analysis equipment that is specific to the focus area of the study.	Can analysis the environmental impact on the river at the basin scale by including multiple. Able to focus on a specific characteristic of the river or a wide range of characteristics. The method can detect slight changes in the river because the focus area can be specified. Takes seasonality into account meaning it can detect changes that occur over an extended period	In developing countries, some MHP are in remote areas which can be difficult to access for sampling. It can be difficult to acquire the required equipment in developing countries	[22]

Before-After Control-Impact (BACI)	Using data collected before the dam is constructed and comparing it to dam collected after the construction of the dam	The data requirements depend on the environmental impact being evaluated	Allows for an accurate comparison of the changes caused by the operation of an HP. Seasonality is taken into consideration if the study takes place over a period.	If the study uses online data, it might be difficult to access in developing countries. It might be difficult to access the dam for in-situ sampling if the dam is in a remote region. The method cannot be applied remotely.	[8,23,24]
			Modelling		
Dendritic Connectivity Index (DCI)	Analyses the longitudinal connectivity of a river network by computing a value between 0 (disconnected) and 1 (fully connected)	Locations of dams. River network of the basin. Digital Elevation Model	The data that is required is easily accessible and the method can be applied remotely which is ideal for application in developing countries. Evaluates the environmental impacts at a basin scale. The method can be applied remotely.	The method assumes the probability of a fish passing a dam is independent of it passing another in a basin. The method cannot focus on the environmental impacts of a single dam	[25,26]
Catchment Area-based Fragmentation Index (CAFI)	A metric to assess the river fragmentation of a basin by using a catchment area	River network. The catchment area of the basin. Location of dams	The data that is required is easily accessible and the method can be applied remotely which is ideal for application in developing countries. Evaluates the environmental impacts at a basin scale. The method can be applied remotely.	There is a limited amount of literature that applies this method in practice and therefore the reliability is questionable	[27]
Population Connectivity Index (PCI)	Analyses the longitudinal connectivity of a river network by computing a value between 0 (disconnected) and 1 (fully connected)	Data relating to fish species in the basin. River network. Location of dams	The data that is required is easily accessible and the method can be applied remotely which is ideal for application in developing countries. Evaluates the environmental impacts at a basin scale. The method can be applied remotely.	There is a limited amount of literature that applies this method in practice and therefore the reliability is questionable. The method estimates the distance fish travel which can make the results inaccurate if the data is inaccurate	[28]
Integral Index of Connectivity (IIC)	Analyses the longitudinal connectivity of a river network by computing a value between 0 (disconnected) and 1 (fully connected)	Data relating to fish species in the basin. River network. Location of dam	The data that is required is easily accessible and the method can be applied remotely which is ideal for application in developing countries. Evaluates the environmental impacts at a basin scale. The method can be applied remotely.	Requires information relating to the distance fish travel which can be difficult to find in developing countries. The method estimates the distance fish travel which can make the results inaccurate if the data is inaccurate	[29,30]
RIVERCONN	Computes multiple river connectivity indexes such as DCI, PCI and IIC to assess the river connectivity of a river basin and suggest the removal of certain dams that would increase river connectivity	Data relating to fish species in the basin. Location of dams. River network of the basin. Outline of basin	The data that is required is easily accessible and the method can be applied remotely which is ideal for application in developing countries. Evaluates the environmental impacts at a basin scale. This method allows the computation of multiple indexes at one time. The method can be applied remotely.	There is a limited amount of literature that applies this method in practice and therefore the reliability is questionable. The method estimates the distance fish travel which can make the results inaccurate if the data is inaccurate	[31]

Analysis and Applicability of Methods

Some factors were used to evaluate each method for applicability in Nepal. If the literature applying the method focused on small hydropower, then the method needed to be evaluated for its scalability to ensure it could be applied at the micro-scale. Furthermore, the size of the hydropower plants means that if there are environmental changes then they may be slight changes. This meant that a suitable method needed to be able to detect minute changes which led to the sensitivity of the method being evaluated. Additionally, Nepal is a data-poor country meaning a method that requires substantial amounts of data would be difficult to use in Nepal. This was the reason the data requirements of the method were evaluated. Lastly, because these hydropower plants can be in remote regions of the country, the accessibility of the method needs to be considered. This meant that a suitable method would either be a remote method or involve equipment that could be easily transported to the location of the study. To summarise, the scalability, sensitivity, data requirements and applicability were the factors used to evaluate the methods.

Each method in Table 2 was compared with the criteria for the method's suitability for application. Focusing firstly on the Time-Series Analysis methods, IHA is a method that requires daily flow data spanning before and after construction of the HP [14,15,16]. This means that in a country like Nepal where daily flow data is difficult to access, finding a location that has pre- and post-construction data is unlikely, therefore, making it difficult to apply this method in Nepal. Also, the scalability and sensitivity of the method are unknown because no literature could be found applying the method to an MHP. However, the method can be applied remotely meaning if the required data became available the method has the potential for application in Nepal. The INSTANT method uses sub-daily flow data [16,17,18], the same problem occurs regarding the availability of data in Nepal. However, INSTANT would be more sensitive than IHA in sensing minute changes in the river flow because sub-daily flow data is used compared to IHA which uses daily flow data. On the other hand, only one paper could be found applying the INSTANT method which questions the reliability of the method. In addition, just like the IHA method, finding the required data in Nepal would be difficult and therefore this method would not be suitable for application in Nepal.

For the In-situ Sampling and Analysis methods, most are similar apart from differences in the length of the study and the number of locations included in the study [8,12,19,20,21,22,23,24]. Aside from this, comparing the methods with the criteria these methods fulfil a lot of the criteria. They can be scaled to the size of the dam included in the study while also being able to detect slight changes in the river. The only negative aspect relates to the applicability of the method. The location and the time the samples are taken are vital. The dam needs to be easily accessible for the equipment to take samples. Additionally, the samples need to be taken once the dam has been constructed and ideally during various times of the year to account for seasonality. A majority of the MHP are in remote regions of Nepal which can make this type of method difficult to apply. However, the purpose of the MHP in Nepal is to provide electricity to the local communities meaning there must be some level of access, making it possible to apply the method. Nevertheless, this method of collecting in-situ samples and analysing them either on-site or in a lab seems to provide the ideal study to assess the environmental impacts of MHP.

Progressing to the last category, the methods that model the impacts of dams and other types of man-made barriers across the river. All the methods included in Table 2 focus on assessing the river connectivity of a basin with dams in operation. An extensive amount of literature was found regarding the different river connectivity indexes that could be used for the assessment.

One method that stood out was RIVERCONN, it allows multiple indexes to be computed for a study area [31]. It allows for the comparison of the index values and an analysis of the dams that could be removed to improve connectivity which was not found in any of the other literature. This method can be applied remotely using data that is easily available from several data sources. This makes RIVERCONN suitable for application in Nepal based on the data requirements and because it can be applied remotely. However, there is only one paper applying this method to a basin meaning there are uncertain areas. To begin with, there is only one case study applying the method meaning the scalability and sensitivity of the method are unknown. In addition to this, the reliability of the results must be questioned as this method was only published in 2022 [31]. Considering these uncertainties, a series of case studies were undertaken in the UK, to understand more about the scalability and sensitivity of the method. The following section discusses these, the relevant study area, data collection, setting up the analysis and the results of the case studies.

RIVERCONN CASE STUDY

Methods

RIVERCONN is an R software program that computes river connectivity indexes for a river basin. The indices that were chosen to be computed in the following case studies included the Dendritic Connectivity Index (DCI), the Integral Index of Connectivity (IIC) and the Population Connectivity Index (PCI). All three of these indexes analyse the longitudinal connectivity of a river network by computing a value between 0 and 1 where 0 shows no connectivity and 1 means fully connected. There are additional indices that can be computed by the software; however, these indices were found to be the most fitting for the study area, see [31] for the other index options. The reason these indexes were chosen was because they produce results using the same scale (between 0 and 1) which allows the results to be compared. Additionally, these were the indexes that were used in the Baldan et al. [31] tutorial. By using the same indexes, the validity of the results could be compared with the tutorial. It was decided the case studies were to be carried out for river basins within the UK as the data required for RIVERCONN was easily available. The methodology that was used to carry out the following case studies was based solely on the RIVERCONN tutorial provided by Baldan et al. [] Where possible the same data sources were used to ensure reliable results were produced.

Data Collection. The data requirements of RIVERCONN include the following: a river network shapefile for the study area, a shapefile for the basin or catchment of the study area, and a shapefile containing the locations of the dams. The shapefiles for the river network system and river basins for the UK were gathered using Hydro SHEDS [32], and Hydro BASINS [33] respectively. The shapefile for the dams across the UK was provided by AMBER [34] which was a recommended source of data from the author of RIVERCONN. Once the data was collected, ArcGIS 10.7.1 was used to view the data and decide on the locations for the case studies [35].

Study Area. Four locations were found to be suitable for analysis, the river basins can be seen in Figure 2. Each one was given a name based on a city, village or general area name located inside each basin. The river basins range in size which allows an evaluation of the scalability of RIVERCONN. The number of dams varied in each river basin to assess the sensitivity of the software. An additional feature of AMBER includes the categorisation of the dams displayed by the database. From this, the average type of dam in each basin was determined and found to be weirs. A weir is used to control the water level of the river and is often used to provide a constant flow of water to ROR dams. [36] discusses the cumulative impacts of weirs on fish and fauna at multiple locations across the UK. The findings of this paper influenced the decision of the upstream and downstream passability in the 'Setting up the Analysis' section.

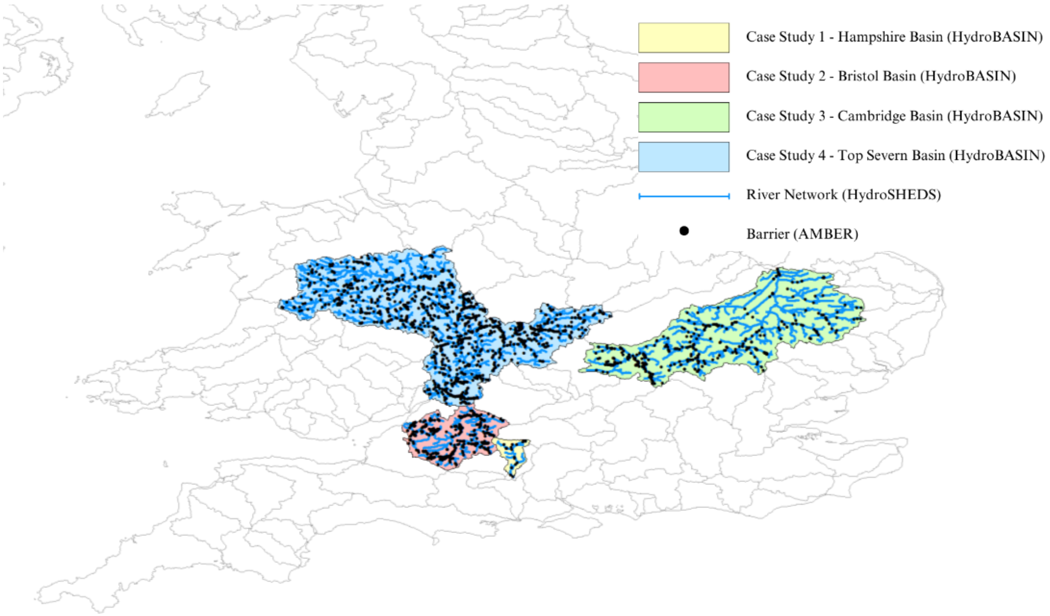


Figure 2. Map showing the location of four study areas used in the analysis of river connectivity within the UK using RIVERCONN.

Setting up the Analysis. Once the case study locations were decided, shapefiles for the river network, the shape of the basin and the location of dams were created for each of the four study areas. This involved, creating three separate shapefiles for each basin, one for the river network, the basin, and the location of the dams. Following this, the code for the index calculations was made specific to each study area. The DCI was computed with symmetric and asymmetric passabilities. The passability is the probability of a fish travelling upstream (pass_u) and downstream (pass_d), if they are symmetrical then equation pass_u is equal to pass_d, however, if they are asymmetric then pass_u and pass_d are not equal.

For the DCI it needed to be determined whether a potamodromous or diadromous calculation was carried out. This relates to the movement of fish in the river, if a fish is potamodromous then it will travel solely within freshwater. However, if the fish is diadromous then it will travel between freshwater and saltwater. The NBA Atlas [37] was used for each case study to determine the five most common fish species in the study area. The Woodland Trust [38] was used to determine if the fish migrate within freshwater or migrate between freshwater and saltwater as this determined whether the fish were potadromous or diadromous, respectively. The most common type of fish, potamodromous or diadromous, was determined which influenced the decision of whether to use the DCI for potamodromous fish (DCIp) or DCI for diadromous fish (DCId) was made. It was found for each case study the DCIp was the most suitable because the most common fish species was a potamodromous fish.

The second index computed was the IIC which can be computed where the weighting of the index uses river reach lengths or with uniform weights. For the first case, there are multiple factors contributing to the computation of the IIC such as the length of the river reach and the habitat suitability index (HSI) and for the second case the only contributing factor is the presence of dams. For IIC and IIC with uniform weights the dispersal parameter (param) needed to be determined. The dispersal parameter is a probability value related to how likely a fish is to travel 10km. The five most common fish species in each study area were used as the basis to determine the correct dispersal parameter to use. [28] provided the dispersal parameter values for each study area, which can be found in Table 3.

The last index calculated for the RIVERCONN model was the PCI. This index can be computed for low-altitude organisms and high-altitude organisms. RIVERCONN computes the Habitat Suitability Index (HSI) which determines how suitable a habitat is for low-altitude and high-altitude organisms. It does this using the digital elevation model that is part of the Hydro SHEDS [32] river network shapefile. The results of the HSI calculation showed that the altitude of each study area was more suitable for organisms that prefer low altitudes. As a result of this, it was decided the PCI was to be computed for low-altitude organisms only. The PCI was computed for symmetric and asymmetric dispersal parameters. The dispersal parameter is the same as the IIC dispersal parameter. Meaning it relates to the probability of a fish travelling 10km. If the dispersal parameter is symmetric *param_u* is equal to *param_d* however, if the dispersal parameter is asymmetric then equation *param_u* is not equal to *param_d*. Where *param_u* is the upstream dispersal parameter and *param_d* is the downstream dispersal parameter. Specific terms are used in the code for the upstream dispersal parameter and the downstream dispersal parameter. The values inputted into the code for each study area are shown in Table 3. The IIC *param* and the PCI *param_u* used the same values which were determined using Rodeles, Galicia and Mirand [28]. However, for the asymmetric dispersal parameter, the *param_u* value was reduced by 0.2 for each case study to simulate an increased difficulty for fish travelling upstream. These decisions were made using Jubb et al. [36]. Once the code for each case study was specialised using the choices made in Table 3, the code was run, and the results were plotted. The plots were generated by the RIVERCONN code from Baldan et al. [31].

Table 3. Decisions made to specialise the RIVERCONN code for each case study.

Study Area	Threshold	pass_u	pass_d	IIC	IIC with Uniform Weights	PCI with symmetric dispersal	PCI with asymmetric dispersal	
				param		param_u	param_d	
Hampshire	-	0.4	0.8	0.5	0.5	0.5	0.3	0.5
Bristol	20	0.4	0.8	0.6	0.6	0.6	0.4	0.6
Cambridge	-	0.4	0.8	0.7	0.7	0.7	0.5	0.7
Top Severn	48	0.4	0.8	0.7	0.7	0.7	0.5	0.7

Results

RIVERCONN produces plots showing the study area and the processes that are undertaken to compute the river connectivity indexes. The following plots were selected to be included in this paper because they focus on the results of the RIVERCONN program. The study area plot of the basin including the river network, outline of the basin and the locations of the dams provides an overview of the study area with the locations of each dam along the river network. The index calculations plot displays the river connectivity of each reach within the river network and multiple indexes allow for an evaluation of the sensitivity of the index and the different parameters included in the index. The dam prioritization plot ranks the dams with the 1st being the dam most likely to improve river connectivity if removed and this allows an overview of which dams should be recommended for removal to improve river connectivity. This provides an idea of the dams which are having the greatest environmental impact on the river basin.

Case Study 1 Hampshire River Basin. The results of the Hampshire River Basin case study can be seen in Figures 3, 4 and 5. There are 9 dams in the basin with a majority being weirs. The location of the dams, the river network and the outline of the basin can be seen in Figure 3. Figure 4 displays the 6 river connectivity indexes that were calculated for the basin, the DCI, IIC and PCI. For each index, the minimum value for the connectivity was below 0.1 which tended towards the tributaries of the river network suggesting the fish species inhabiting the river struggle to access those points in the basin compared to the main river channel. The DCI indexes suggest a greater level of connectivity across the basin with the highest level of connectivity being between 0.6 and 0.8. However, the IIC and PCI indexes all suggest a more fragmented river basin with values of 0.3 to 0.5 begin the greatest value of river connectivity. For the DCI, the range of the index values is quite significant, ranging from 0.1 to 0.8. However, the IIC and PCI index range from 0.1 to 0.5. The difference in results of the DCI, the IIC and the PCI brings forward the question of how accurate the results of the DCI are compared to the IIC and PCI. This may suggest the DCI is not as valid as the IIC and PCI. Focusing on the ranking of each dam, Figure 5, a trend appears across the indexes, all apart from the IIC with uniform weights appear to have computed the same ranking for each of the dams. The dams that were ranked the highest for prioritised removal were located along the main river channel. This shows a strong correlation between the results of the indexes as they produce comparable results showing a level of reliability within the results. Overall, this basin shows an elevated level of river connectivity with only a few areas that are cause for concern which is due to the small number of dams located in the basin. If several of the dams with the highest ranking for removal were removed, then it is possible the river connectivity of the basin would be restored to a higher level of connectivity. This then suggests that dams are having a negative environmental impact on the river basin by reducing the river's connectivity.

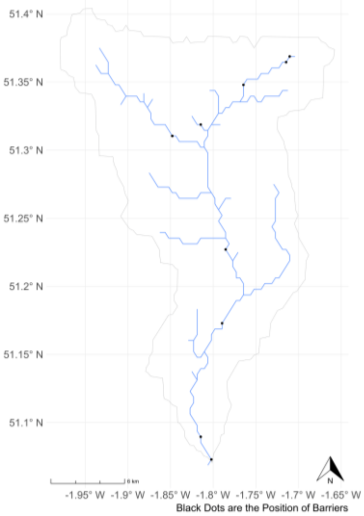


Figure 3. Hampshire Study Area including the outline of the basin, the river network, and the locations of the dams.

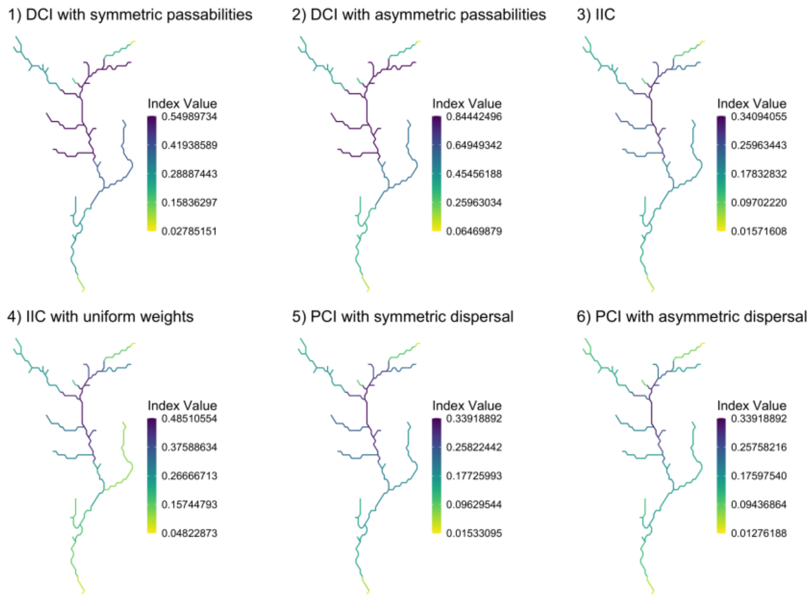


Figure 4. River Connectivity Index Calculations for the Hampshire Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

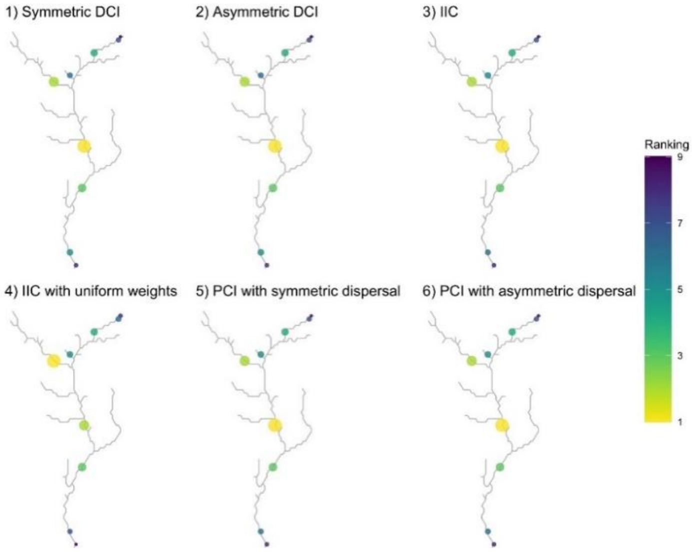


Figure 5. Dam Prioritization for Hampshire Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

Case Study 2 Bristol River Basin. The second case study was the Bristol River Basin which has 154 dams, most of which are weirs. The study area can be seen in Figure 6 and includes the river network, basin outline and location of the dams. Figure 7 displays the index calculations for the six indexes used for the analysis which all show elevated levels of river fragmentation across the basin with a maximum value of 0.3 from the DCI with asymmetric passabilities and a minimum value of 0.002 from the PCI with asymmetric dispersal. This level of river fragmentation across the basin suggests that fish species inhabiting the river within the basin struggle to travel across the basin due to the presence of dams. As with the Hampshire basin, the DCI suggests a slightly increased level of river connectivity compared to the other indexes. Comparing the maximum values of the DCIs with the other indexes, there is an increase of approximately 0.1 and 0.2, respectively. This difference is minimal but should be noted as the IIC and PCI both have similar maximum and minimum values suggesting more reliable results between them as they support one another. Focusing on the dam prioritisation, in Figure 8, all indexes show the dams located along the main river channel hold the highest prioritization for removal. It is interesting to note the areas of the basin with lower levels of river connectivity are not the same areas where the dams are prioritised for removal. A potential reason for this is RIVERCONN wanting to prioritise increasing the connectivity of the main river channel. This hypothesis should be compared with the other case studies to test it. Overall, the Bristol River Basin shows elevated levels of river fragmentation focused mainly on the tributaries of the basin. This showed that it is possible for the fish inhabiting the basin to travel through the basin with difficulty.

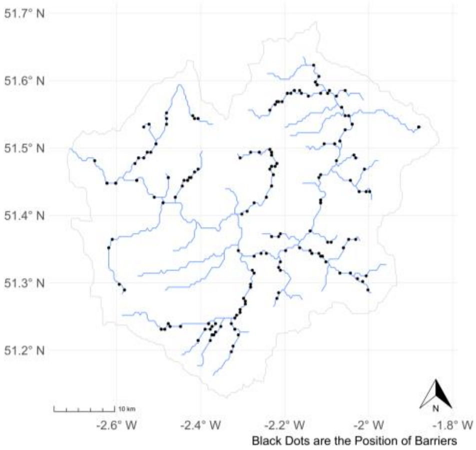
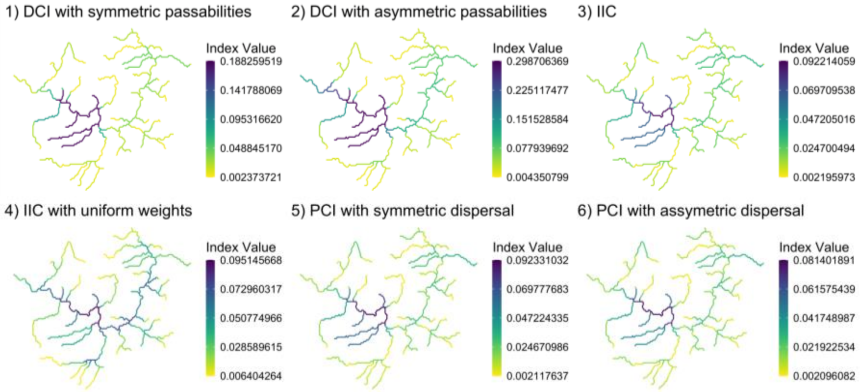


Figure 6. Study Area for Bristol Basin including the outline of the basin, the river network, and the locations of the dams.


1) DCI with symmetric passabilities

2) DCI with asymmetric passabilities

3) IIC

4) IIC with uniform weights

5) PCI with symmetric dispersal

6) PCI with assymetric dispersal

Figure 7. River Connectivity Index Calculations for Bristol Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index

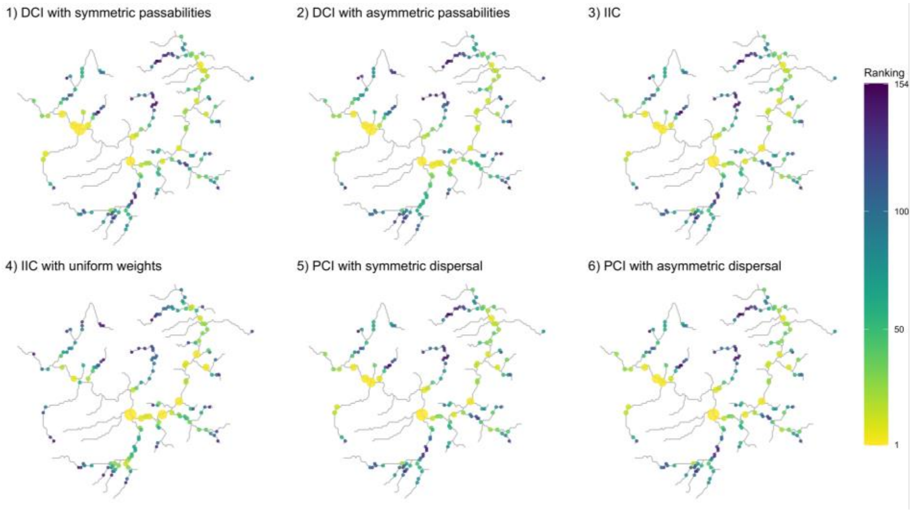


Figure 8. Dam Prioritization for Hampshire Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

Case Study 3 Cambridge River Basin. The third case study using RIVERCONN was the Cambridge River Basin which can be seen in Figure 9 along with the locations of the dams within the basin. Focusing on Figure 10 there is a great deal of river fragmentation along the tributaries of the river basin. This was expected because of the high number of dams located along the tributaries of the river. It can be seen in some sections of the rivers there are multiple dams on a single section of the river which has reduced the river connectivity significantly. Moving on to the main river channel, there is a higher level of river connectivity in that part of the basin. This is due to the reduced number of dams in that section of the basin. However, the index values for each of the indexes suggest that the basin is extremely fragmented with the values ranging from 0.8x10^4 from the PCI to 0.5 from the DCI with asymmetric passabilities. There is a clear correlation between the connectivity values of the IIC and PCI. The DCI does have similar findings, with the DCI with symmetric passabilties showing a similar scale to the IIC and PCI, however, the DCI with asymmetric passabilties suggests better connectivity compared to the other indexes. This finding does not carry through to the dam prioritisation seen in Figure 11, as each index concurs with the same ranking. The dams which have the highest ranking are those which are located along the main river channel within the basin. Interestingly, the dams located in the tributaries of the basin where the most amount of river fragmentation occurs are ranked the lowest priority for removal. This supports the hypothesis proposed in the Bristol Basin results. Comparing the Bristol Basin and the Cambridge Basin, the Bristol Basin has 154 dams, and the Cambridge Basin has 141 dams. Even though the Cambridge basin has a smaller number of dams in the basin, it has a significantly higher amount of river fragmentation when compared to the Bristol basin. It is unclear the reason behind this, but it does show that more research is required into this method to understand this. Overall, the RIVERCONN has shown that the Cambridge River basin has an elevated level of river fragmentation across the whole basin. This reduction in river connectivity will impact the movements of fish and fauna inhabiting the basin which in the future may start to cause ecological impacts to the surrounding areas. Comparing the Bristol Basin and the Cambridge Basin, the Bristol Basin has 154 dams, and the Cambridge Basin has 141 dams. Even though the Cambridge basin has a smaller number of dams in the basin, it has a significantly higher amount of river fragmentation when compared to the Bristol basin. It is unclear the reason behind this, but it does show that more research is required into this method to understand this. Overall, the RIVERCONN has shown that the Cambridge River basin has an elevated level of

river fragmentation across the whole basin. This reduction in river connectivity will impact the movements of fish and fauna inhabiting the basin which in the future may start to cause ecological impacts to the surrounding areas.

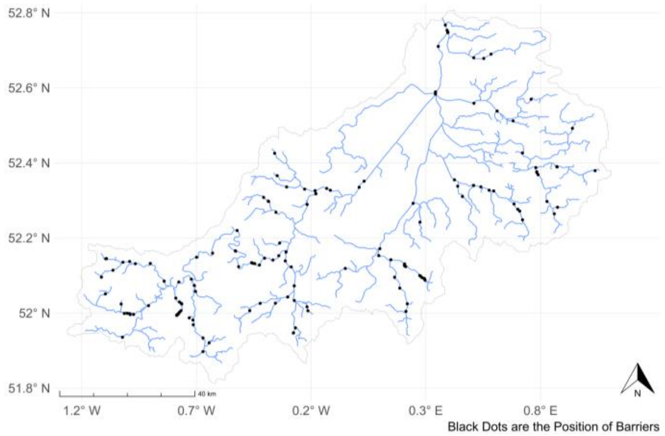


Figure 9. Study Area for the Cambridge Basin including the outline of the basin, the river network, and the locations of the dams.

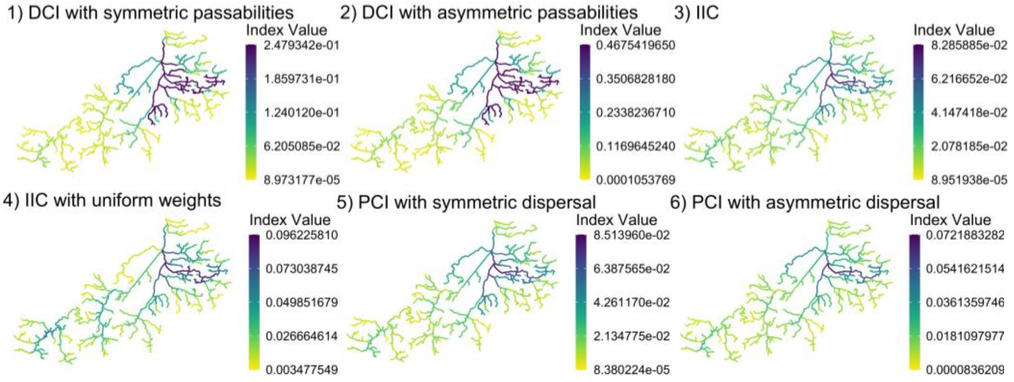


Figure 10. River Connectivity Index Calculations for the Cambridge Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

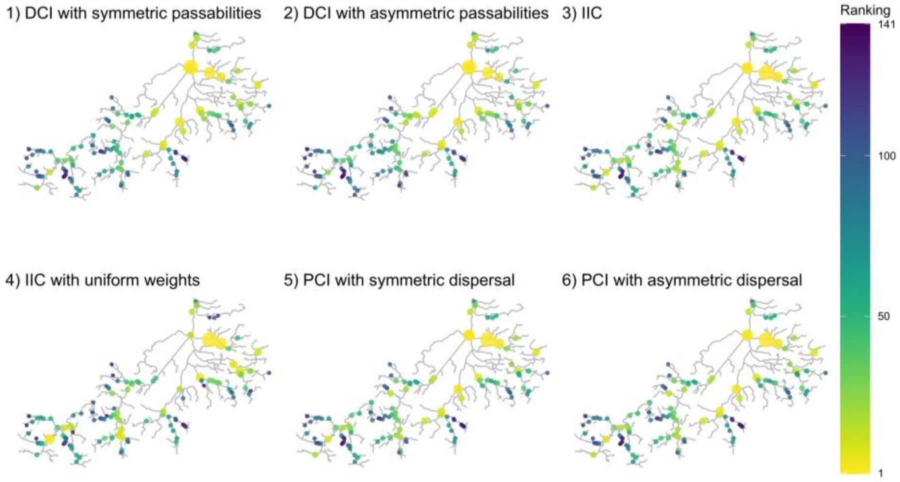


Figure 11. Dam Prioritization for Cambridge Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

Case Study 4 Top Severn River Basin The study area for the Top Severn Basin can be found in Figure 12 including the outline of the basin, the river network and the location of the dams, there are 358 dams in the basin. Figure 13 shows the index calculations for the basin, showing a great deal of river fragmentation. Each index shows a minimum connectivity value of around 0.0006, apart from the IIC with uniform weights which had a minimum value of 0.003. However, even though the IIC with uniform weights had the greatest minimum connectivity value, it had the smallest maximum connectivity value at 0.04. Both DCI indexes had a maximum connectivity of 0.1 and the IIC and PCI indexes had a maximum value of around 0.4. Overall, the results of each index suggest the basin is extremely fragmented. Areas with the lowest levels of connectivity are located along the tributaries of the river. This was expected due to the high density of dams in those specific areas. Looking at the dam prioritization, Figure 14, the areas with the highest ranked dams are located along the main river channel and in the tributaries located towards the top of the basin. It is interesting to note the dams that are prioritised for removal are in the areas with higher levels of river connectivity. This also supports the hypothesis that the Bristol Basin which is RIVERCONN may be prioritising the connectivity of the main river channel over the tributaries. Overall, the Top Severn Basin was the largest basin out of all four case studies and shows elevated levels of river fragmentation across the basin. All six indexes show a similar pattern of fragmentation along the main river channel and tributaries of the basin as well as the ranking of dams for removal. There is a clear indication of reduced connectivity within the basin which will impact the movement of the fish and fauna inhabiting the rivers within the basin.

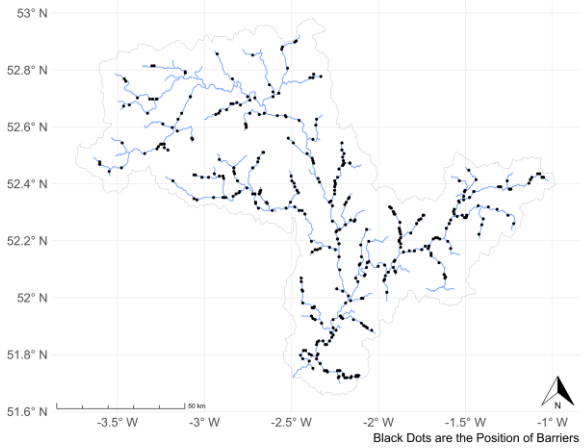


Figure 12. Study Area for Top Severn Basin including the outline of the basin, the river network, and the locations of the dams.

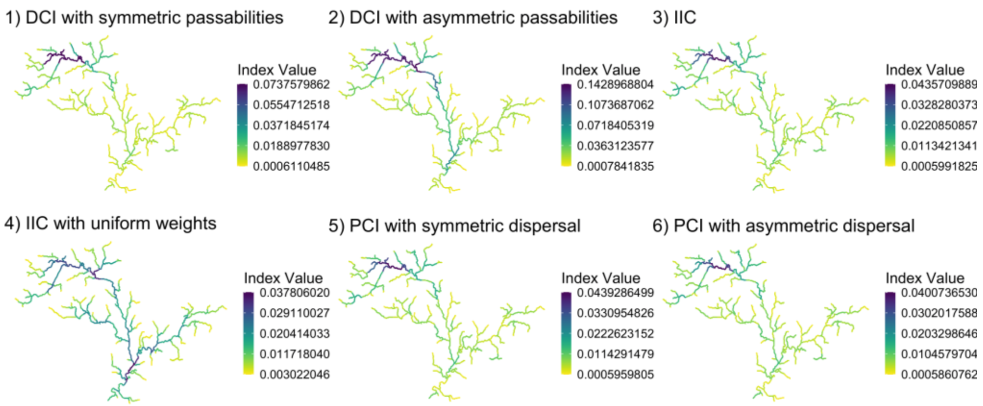


Figure 13. River Connectivity Index Calculations for the Top Severn Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

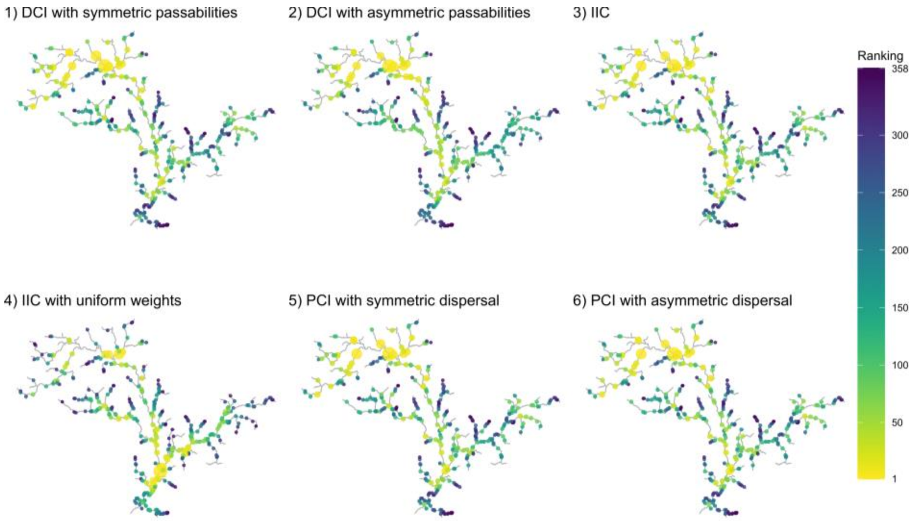


Figure 14. Dam Prioritization for the Top Severn Basin. DCI: Dendritic Connectivity Index; IIC: Integral Index of Connectivity; PCI: Population Connectivity Index.

DISCUSSION

The results of the four case studies provided useful insight into the application of RIVERCONN. It was able to compute the river connectivity values for three types of indexes, the DCI, IIC and PCI as well as prioritise the removal of certain dams to improve river connectivity for four study areas in the UK. Each study area varied in size and the number of dams within the basin. Across the four basins, there were elevated levels of river fragmentation with the most reduced connectivity located along the tributaries of each basin which was caused by the dams within the basin. Reduced river connectivity changes the way water flows through the basin impacting the ecosystem, the flow of sediments and nutrients in the river. This shows the relationship between dams and environmental impacts. The presence of dams in a basin causes an environmental change by fragmenting the rivers within the basin.

At each basin size, RIVERCONN was able to produce clear results showing that the software is capable of scalability. In addition to this, the software was able to analyse each basin with the varied number of dams without issues showing the number of dams in a basin does not impact the useability of the software. The software allows the type of dam to be specified, however, due to time constraints the dams in each basin were not specified. Instead, it was assumed all the dams were weirs which was indicated by AMBER which was the data source used for the location of the dams. However, with additional information, it is possible to specify each dam’s passability depending on the type of dam. This may be a limitation of the results of the case studies and for application in Nepal, specifying the type of dam should be considered. Moreover, RIVERCONN is a software which requires data that is readily available from multiple data sources. This is extremely important when trying to find a method to use in Nepal as one of the greatest limitations is data availability. The software was developed in 2022 and there is limited literature related to the application of the software. This means there is the possibility the results of the four case studies are not accurate. Despite this, considering the results of the UK case studies are like the results of Baldan et al. [31], the overall conclusion is that the results are valid. Additionally, the indexes that were used in RIVERCONN have been used in multiple case studies over the past decade also adding to the validity of the results. Overall, RIVERCONN is suitable for application in Nepal based on the results of the UK case studies. This is because the software is capable of being used for any size basin and any number of dams. Furthermore, the software can account for the types of dams that are in the basin which is important as it allows for more accurate results. Finally, the data requirements of the software imply the software can be used in data-poor countries such as Nepal without any problems. To conclude the many benefits of RIVERCONN mean it is suitable for application in Nepal to assess the impacts of MHP on river connectivity.

Additionally, another method fulfilled all the criteria for being suitable for application in Nepal. The method involving in-situ sampling and analysis was found to be suitable because it can be applied at the micro scale by taking samples along the study area. By analysing samples, the method can detect minute changes, meaning it has the required sensitivity for application. Furthermore, the method does not require pre-existing data and can be carried out using minimal equipment which means that it can be applied in a data-poor country like Nepal and in remote regions where the MHP are located. As the method of in-situ sampling and analysis fits all the criteria for a method to be suitable for application in Nepal, it is concluded that it is suitable for application in Nepal to assess the environmental impacts of MHP.

CONCLUSION

Nepal is a data-poor country with micro-HPs that are a fraction of the size of impoundment HPs. Often these MHP have no storage capacity and operate on a run-of-river basis in remote areas across the country [10,12]. There is a current assumption that these MHP do not cause any changes to the environment, however, thorough research suggests this assumption might not be true [4,7,11]. There is a need to question this assumption and find out whether MHP cause changes to the environment [12]. The method in which to do this provides a challenge because of the size, location, and data availability of the MHP’s. The purpose of this paper was to evaluate methods for their suitability for application to investigate the environmental impacts of MHP in Nepal.

Through extensive research, methods with the potential for application in Nepal were found and evaluated. These methods included in-situ methods and remote methods including Time-Series Analysis, In-Situ Sampling and Analysis and Modelling. After evaluating each method regarding the scalability, sensitivity, data, and accessibility requirements there were two methods which stood out to be the most suitable for application in Nepal. The first method was in-situ sampling and analysis which is an in-situ method where samples are collected and analysed either on site or in a laboratory. The method could be scaled down to the MHP, is capable of detecting minute changes in the river and only requires sampling and analysing equipment which can be procured. The only negative aspect of the method is accessing the MHP as they can be difficult to access meaning choosing the right location would be vital [12,19,22]. The second method was a remote method, RIVERCONN which can be scaled from a small basin to a large basin and can be specialised for the type of dams within the basin. Additionally, the data required can be accessed easily and the method can be applied remotely [31]. Both methods allow for an accurate evaluation of the environmental impacts of MHP in Nepal.

It was decided that four case studies were to be conducted in the UK using RIVERCONN because there was little literature using the method and the accuracy of the method needed to be validated. For all four case studies, it was found there was a significant reduction in river connectivity in the basins. The findings suggest that the operation of weirs has a significant negative impact on the connectivity of the river network, which supports the findings in [36]. This method also showed there is a cumulative impact on the river caused by dams which poses the question, if there are cumulative impacts, shouldn't there be individual impacts? Furthermore, the research in this paper supports [4,7,11] review papers which concluded there was a need for more research into the environmental impacts of ROR dams. It is possible that the assumption is correct, and the changes that have been found are small enough to be considered negligible. There are limitations within this paper, including the fact that RIVERCONN has only one published paper applying the method; therefore, the results may not be reliable. Many of the papers found focused on ROR dams where the generation capacity was not specified, making it uncertain if the findings of those papers apply to this research area. Lastly, additional methods were found during the initial literature review. However, due to time constraints, these methods were not the focus. Future research should apply the method recommended in this section. Applying both in-situ sampling and analysis and RIVERCONN would provide the opportunity to evaluate the environmental impacts of specific MHP and the MHP within the basin.

ACKNOWLEDGMENT

The author would like to acknowledge to supervision of Dr. Sam Williamson and Dr. Colin Nolen and the help of Dr. Damiano Baldan who supported the use of RIVERCONN.

NOMENCLATURE

MHP – Micro Hydropower Plant
HP – Hydropower Plant
ROR – Run-of-River
IHA – Indicators of Hydrological Alteration
INSTANT – Instantaneous Streamflow Analysis Tool
BACI – Before-After Control-Impact
DCI - Dendritic Connectivity Index
CAFI - Catchment Area-based Fragmentation Index
PCI - Population Connectivity Index
IIC - Integral Index of Connectivity
Pass_u – upstream passability
Pass_d – downstream passability
DCIp – Potadromous Fish
DCId – Diadromous Fish
Param – Dispersal Parameter
HSI – Habitat Suitability Index
Param_u – Upstream Dispersal Threshold
Param_d – Downstream Dispersal Threshold

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