A PROTOTYPE EXPERT SYSTEM FOR FISHWAY DESIGN

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(Received June 1991)

Abstract. The design of structures for fish passage in rivers and streams provides an opportunity to apply expert system concepts to a design problem. Fishways contribute to the sustainable development of water resources projects by providing a path that allows fish migrations to be maintained. A prototype expert system (FDES) has been developed to recommend the most suitable fishway type for given design conditions. A recommendation is provided on the basis of fishway hydraulics, fish passage performance, and cost requirements. Fishway design demands expertise in various scientific disciplines such as hydrology, hydraulics, and fish biology. Expert system technology may be used to reduce design time requirements and to serve as a teaching aid to inexperienced engineers by organizing and accessing the cumulative knowledge of the most experienced designers. The rule-based expert system development tool, VP-Expert, supplies the backward chaining control structure for accessing the knowledge within the prototype.

1. Introduction

1.1. Fishway Design Problem

Fish migrations in rivers and streams involve cycles of upstream and downstream movements for spawning and feeding. This migration may be hindered, or prevented, by obstructions such as dams, weirs, roads and other man-made or natural restrictions. Fishways are hydraulic structures that enable fish passage upstream of an obstruction. Their design includes several major categories. The most common are: culvert, pool and weir, vertical slot, and Denil fishways.

Culvert fishways are culverts of various shapes with baffle arrangements spaced along the bottom to help dissipate water energy and reduce fishway velocities to enable easier fish passage. Denil fishways, named after their inventor, are rectangular chutes with closely spaced baffles that run along the edge of the chute. Vertical slot fishways are also rectangular chutes but are separated into resting pools by baffle configurations that allow fish passage through a slot (Rajaratnam *et al.*, 1986). Weir fishways, including orifice types, are chutes separated into a series of resting pools by weirs that require fish to jump over the weir or swim through an orifice at the bottom of the pool.

In the design of a fishway, important factors to be considered include the hydraulic

Environmental Monitoring and Assessment **23**: 115–127, 1992.
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characteristics of the fishway type, as well as the swimming performance and behaviour of the species of fish to be passed. Biological and hydraulic criteria for designing fishways vary with species and sizes of fish. Fishway efficiency depends on attraction, as well as the safe and speedy transport of fish. Attracting to the fishway entrance is critical and depends on species behaviour and motivation.

In fishway channels, fish transport relies on water velocities not exceeding the swimming abilities of the migrating species. Swimming ability varies with species and size, as well as water temperature, oxygen, pH, and salinity. Water velocities depend on fishway type, channel slope and water depth. Velocities and depths are functions of fishway discharge and slope. The most important factor in selecting the type of fishway to be used is the record of experience with the species of fish it is desired to pass (Bell, 1984; Clay, 1961; Katopodis, C.: 1990, 'Introduction to Fishway Design', Internal Report, Department of Fisheries and Oceans, unpublished).

The design of fishways has been a necessary engineering task for many years but advanced development of this expertise has only occurred very recently (Katopodis, 1990). The last 15 years have seen advances in fishway technology through structured experimentation, analysis, and the collection of extensive field data from actual fishways. An application of expert system (ES) technology to fishway design could prove to be a valuable design tool for experienced engineers as well as a teaching aid for novice engineers.

1.2. Design Practice

The design of fishways is concerned with the preservation of the migratory habits of fish species for various commercial, biological, and environmental reasons. Problems which can occur with a fishway design include: velocities in the fishway which exceed the swimming abilities of the fish; and low attraction potential for fish at the downstream end, preventing fish from finding the fishway. Fish are attracted to the downstream entrance by flow and high surface velocities.

The design process for fishways can be described in point form (Katopodis, 1990) as given below:

(a) Data accumulation: identify the obstacle that hinders migration; supply detailed mapping of the restricting structure and the surrounding area; provide a list of fish species, population estimates, and length ranges; describe the migration period, including associated water temperatures and peak migrant numbers; show locations of local spawning, feeding, and fish congregation.

(b) Hydraulic analysis: perform a flow frequency analysis for the hydraulic structure that obstructs migration for low, average, and high flows, the structure design flow, and fish passage design flow; prepare stage-discharge relationships for both the headwater and tailwater of the obstruction.

(c) Examine various types of fishways and prepare a short list of feasible options by considering site conditions and hydraulic structures, fish species and sizes, water levels and flows, fish behaviour and stamina (scope of the prototype expert system).

(d) Fishway analysis: prepare a fishway discharge rating curve (without backwater

effects); prepare velocity profiles for the fishway to compare with fish swimming speeds; estimate backwater effects. Note that discharge rating curves and velocity profile regressions have been performed for most standardized configurations (Katopodis, 1990).

(e) Report generation: develop a preliminary design and report; assess the preliminary design through expert advice and prepare a final report.

(f) Follow-up: develop a monitoring program to evaluate the operating performance, and a maintenance program for the fishway.

The fishway analysis may include several design configurations from a variety of fishway types. Generally, the designer initially chooses the type(s) of fishway which typically provide the best cost efficiency and fish passage performance combination. Configurations of the chosen type are compared using dimensionless discharge and velocity parameters that indicate fishway efficiency. One or more design options can then be compared in initial reports to allow easy comparison of varied design approaches.

Each fishway category is unique in its design and analysis approach. One of the most simple is for vertical slot fishways. Design of a vertical slot fishway is performed iteratively by one of two approaches. The first approach selects a vertical slot width at a minimum acceptable value (for passage of the largest expected fish). This defines the scale of the configuration and forces the slope of the fishway to some value that allows an acceptable head drop between resting pools. The slot width is then increased or the slope decreased until acceptable velocities are reached. Note that slope is inversely proportional to the slot width. For the second approach, a maximum acceptable slope is initially chosen and lowered until the slot width is acceptably large.

2. Use of Expert System Technology for Fishway Design

2.1. Motivation for Using Expert System Technology

From the discussion in the Introduction it was decided that ES technology was appropriate for the design of fishways. Multi-disciplinary expertise, and practical experience are necessary for an engineer to produce a good fishway design. Multi-disciplinary knowledge and 'rules of thumb', developed by experienced fishway designers, provide opportunities for using ES concepts to aid in the design process.

A fishway design ES could be a practical office tool for engineers to reduce design times, elicit problem recognition, and promote a greater understanding of the situation at the preliminary design stage. It is very difficult for a novice engineer to produce a good design in a limited time because there are so many factors and rules that may influence the fishway performance. An ES application would be very useful for incorporating the cumulative knowledge of hydraulic and biological fishway aspects and combining them with practical expertise from the most experienced designers to assist the engineer in making decisions about the design approach.

2.2. Expert Systems and Engineering Design

ESs are identified as a way to successfully apply Artificial Intelligence (AI) techniques. Through the application of AI techniques, ESs capture the knowledge needed to assist an

individual when dealing with problems of different complexity (Rolston, 1988). The most powerful characteristic of ESs, making them different from traditional computer applications, is their capability to deal with real-world engineering problems by incorporating engineering judgement and intuition.

ESs were brought to the attention of water resources civil engineers almost a decade ago (Simonovic and Savic, 1989). Applications of ES technology are considered as appropriate and natural since the discipline of water resources engineering contains numerous procedures developed from theory, actual practice, and 'rules of thumb'.

The reviews of ES applications in Civil Engineering (Maher, 1987), in Environmental Engineering (Ortolano and Steinemann, 1987), and in Water Resources Engineering (Simonovic and Savic, 1989) led to the following conclusions: (i) a large number of successful pilot systems indicate the wide range of potential benefits of this technology in engineering planning, design, and operations; (ii) the complexity of engineering fields precludes the development of a general ES approach for a particular field of engineering; (iii) all the reported applications are single programming tool oriented; and (iv) the initial application of ES technology is showing a positive reaction between potential users and experts involved.

According to the documented applications of ESs in water resources, very limited work has been done to support the design process (Strzepek, K.: 1988, Personal communication, Department of Civil Engineering, University of Colorado, Boulder, Colorado; Russell, 1989). The design processes are quite complex, as indicated in the introduction, and involve procedures and knowledge at the same time. According to Russell there seem to be two main phases in the design process: (a) performing the design by selecting the necessary components, determining their size and fitting them to work together; and (b) exploring the design modifications until all the objectives of the designer are satisfied.

The first part of the design process is the creative part. It can be described in a series of steps, but is very difficult to teach except by example. The second part involves a complex set of steps which are needed to create a design which will be economic, safe, elegant, environmentally friendly, and which will still maintain a certain level of reliability.

Although systems analysis (optimization, simulation and multiobjective analysis) could be used to support the design process (for example the optimization can assure that a design is the most economic), the major activities are derived from experience. Because of the complexity of the process and the fact that most of what a designer does is done subconsciously, it is not realistic to expect ESs for design to be developed quickly.

Future efforts will be directed toward developing ES support for the design process. This effort will require an explicit definition of intuitive skills used in the design to provide more effective education for future designers.

2.3. Fishway Design Expert System Prototype

The selected scope of FDES is the problem of determining the best fishway type for specific design conditions. Use of this application has the potential for reducing the number of computations associated with comparing the performance of fishway designs from numerous categories. The fishway design prototype (FDES: Fishway Design Expert

System) recommends the most suitable type of fishway, provides basic design parameters and, in the case of a vertical slot fishway recommendation; chooses a standard configuration and specifies the cross-section dimensions.

To provide a fishway type recommendation, FDES determines the feasibility of different fishway types. Hydraulic and biological data are used to test culvert, pool and weir, vertical slot, and Denil fishways to establish a list of design categories to be considered. The feasible list is then narrowed to one or two choices by comparing fish passage performance and fishway costs of the feasible categories. The scope of FDES is very narrow in terms of the hydraulic expertise that is required in a complete fishway design, but incorporates much of the biological knowledge and experience necessary to ensure adequate fishway performance.

2.4. Expert System Development Tool for Prototype Design

The prototype user interface is supplied by the expert system development tool called VP-Expert (Paperback Software, 1987). The environment is largely controlled by VP-Expert. However, there are a few things that can be manipulated. It was beneficial to use the development tool (expert system shell) to help produce the prototype because program structure within the shell is simple. Pieces of knowledge can be inserted as the expertise is accumulated, without the programmer having to spend a lot of time worrying about strict structural programming requirements.

Unfortunately, VP-Expert has been found to be very limited in performing some of the tasks required by the prototype structure. Any numerical manipulation, such as selecting a minimum value from a list, can be cumbersome and time consuming using the supplied rule format.

3. Description of the Fishway Design Expert System Prototype

3.1. FDES Structure

FDES has three knowledge bases (KB), and is organized in rule format. The program flow is depicted in Figure 1. The first knowledge base (FISHWAY.KBS) is used to process the initial system information in an attempt to quickly cover steps (a) and (b) of the fishway design process (found in the Introduction) and to filter out any unreasonable or unusable data. The second knowledge base (FTYPES.KBS) attempts to complete step (c) by invoking the design criteria and various rules that the expert uses to assess the suitability of the fishway categories and recommends the best type for design. The final stage of the program is the design of a vertical slot fishway cross-section as an illustration of design step (e). It is contained in a FORTRAN program (DESIGN.EXE) that is accessed from FYPES.KBS if vertical slot is a recommended fishway type.

Goals within the two KBs are fairly rigid because the inherent logical process for evaluation is step by step. Several pieces of information are required prior to any recommendation. Head and tail water elevations, and important fish species (to obtain maximum and minimum design lengths) are queried in the first knowledge base. This is general system knowledge that is saved and passed to the second KB which uses the

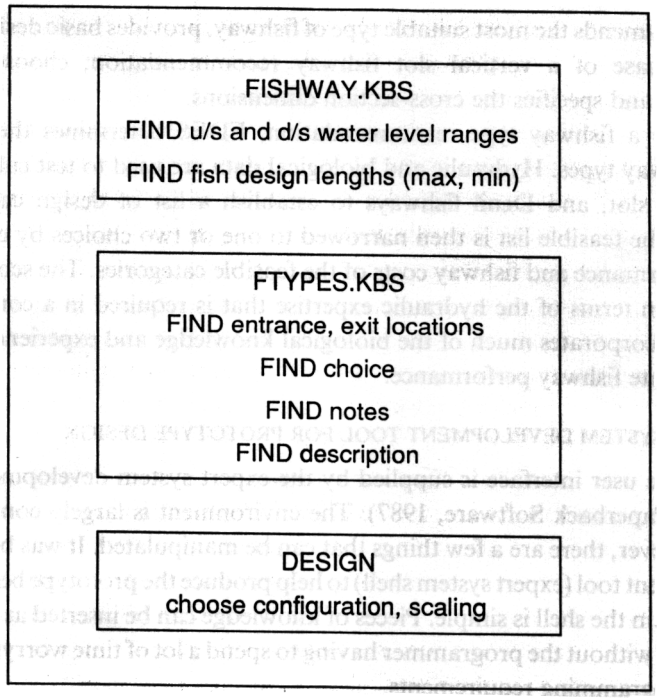

Fig. 1. FDES prototype structure

information to generate questions and obtain a recommendation for the design. The two KBs are separated so that the generation of the recommendation in the second KB can be repeated using different fishway entrance and exit locations without repeating the input of fish types and flow characteristics. Locating the ends of the fishway are decisions that the designer must make with only limited advice from the ES (due to the obvious difficulty of trying to access data about terrain and localized stream flow characteristics).

The goal for the generation of a recommendation is simply to FIND the CHOICE variable which invokes the backward chaining process to find and compare the feasible types. Minor subsequent goals consist of finding relevant NOTES which may be design considerations, or advice in the event of finding no standard solutions.

FTYPES.KBS is broken up into several distinct sections. The variable METHOD uses basic hydraulic criteria to build an initial list of available types of fishway to consider. For example, pool and weir fishways are usually considered when water level fluctuations are less than 0.5 m, the maximum slope is greater than 5%, and the obstruction is not a road crossing.

The variable NMETHOD (narrow method) completes the list of feasible fishways by restricting the METHOD list with physical attributes of the location and biological criteria. Pool and weir fishways are considered feasible if they belong to the METHOD list, and the construction area is sufficient to decrease the slope to a range that is most

commonly conisiderd (between 5% and 15%).

The CHOICE variable generates the recommendation by choosing a feasible type of fishway that is cost efficient (based on previous design construction costs) and which exhibits a high performance in its ability to pass fish. If Denil and vertical slot fishways are both feasible, a Denil is usually chosen but it may be chosen for different reasons. If upstream and downstream water level variations are not reasonably synchronous (that is, the levels may not vary proportionally, in the same magnitude, or in the same time frame) then a Denil is chosen because there may be backwater effects that cause downstream flow in the fishway to be drowned out, reducing fish attraction and making it difficult for fish to find the fishway entrance. Denil fishways provide higher fish attraction by allowing larger flows to pass through the fishway (compared to vertical slots). If water level variations are synchronous, then Denil is chosen based on cost efficiencies associated with simple design dimensions and higher acceptable slopes (shorter fishway length) than vertical slot fishways.

Once a recommendation is given, a list of NOTES is accessed to provide the user with additional advice and design information. If a Denil fishway is chosen, a NOTE recommends resting pool spacing according to the fish species that need to be passed (10 to 15 m for salmon; 5 to 10 m for freshwater fish). The NOTES are also very useful if the design conditions do not yield a recommendation. Suggestions are made to advise the user why no solution is recommended, and what can be done to adapt to the situation. For example, if there is no recommendation, and the maximum slope is very low (0.5 to 5%), then a NOTE informs the engineer that culverts are usually used in this situation but the maximum allowable swimming distance in the culvert may have been violated. The advice in this situation is to provide resting pools to allow the fish to recuperate after a long swim. This is based on limits for swimming performance in a culvert, generally $F=0.5$, where F is a dimensionless velocity parameter. The maximum swimming distance is then found as a function of fish length using regression analysis that relates F to the ratio of distance to fish length for two types of swimming modes that fish commonly use. The value of $F=0.5$ is an experience-based limit supplied by the expert.

If a vertical slot fishway is recommended, relevant design parameters are passed to the DESIGN program which establishes invert elevations at the upstream and downstream ends of the fishway, recommends a suitable height for the fishway, and determines the optimal scaling of the fishway for standard design number 18 (Rajaratnam et al., 1989). Design 18 was chosen based on the comparison of dimensionless discharge rating curves for numerous vertical slot designs. The slope is set to a maximum allowable value and decreased in increments until all design conditions are met. It, in effect, starts at a super optimal state and relaxes performance variables until feasible conditions exist. Design conditions include adequate fishway velocity for fish to swim against, and a wide enough vertical slot for the largest fish to swim through (note: the scale of the fishway are based on relationships with the vertical slot width, b_0).

There are also several error trapping mechanisms built into the two KBs that prevent unreasonable or infeasible data to be entered. This is necessary because some of the variables are numeric values, such as water level elevations, which can not be controlled by

restricting the responses of the user.

3.2. FDES PROTOTYPE DEVELOPMENT PROCESS

3.2.1. *Knowledge Acquisition*

The source of expertise for this project is the second author of the paper, one of the leading experts in the field of fishway design and civil engineering for fish habitat maintenance. He agreed to act as an expert consultant for the development of the prototype with the intention of being exposed to concepts that will advance the development of an ES for fishway design, now in its initial stages of knowledge acquisition and organization at the Department of Fisheries and Oceans. The expert also participated in the prototype verification by evaluating the form of the questions and system output.

3.2.2. *Knowledge engineering*

The prototype was tested extensively on several levels to evaluate the incorporated expertise. Through an iterative process of suggestions and modifications FDES improved enough to perform on an acceptable level of expertise.

The first knowledge base must ask the user for water levels at the upstream and downstream end. This creates some difficulty because the user must have completed several calculations ahead of time and must be able to understand what is needed for the design problem. The assumption used for the programming is that the ES should supply enough information at this prompt to make sure the user has completed the preliminary task properly. The user is then prompted to enter the types of fish that the fishway must pass. The KB includes as many species of fish as possible to provide program flexibility.

When the second KB requests the entrance and exit locations, the screen is arranged to provide advice in a graphical manner to help prevent confusion and frustration. A diagram of the river section in plan view helps the user to visualise the necessary input information.

Any other questions posed to the user are optionally prompted by invoking certain rules. They are designed to be as simple as possible. For example, the question: 'Is the obstruction a road crossing?' is a simple yes or no question that replaces the more logical question: 'Which type of structure is the obstruction?', which has numerous choices. The question can be simplified because the type of fishway depends only on whether or not the obstruction is a road crossing.

The library of notes or advice can be valuable to the designer to evaluate what kind of ingenious adaptation could be used to get a working design in the event of no recommendation. These notes can also inform the designer of design conditions that he may be unaware of such as flow requirements or resting pool spacing.

3.2.3. *Prototype Verification*

Two users and the developer were used to test the ES. The expert evaluated system results, the form of the questions, and the instructions provided with some of the questions. The expert was able to transfer much of his expertise to FDES as modifications were made to

comply with his suggestions. The feedback from the verification process was valuable to the program development by augmenting the expertise extracted from three previous consulations with the expert. The verification enabled the expert to understand the problem scope and approach more thoroughly. As a result, he was able to concentrate on the narrow range of knowledge in the problem scope.

An inexperienced user was also solicited to test the system. His suggestions centred around the display and clarity of the instructions and descriptions. His feedback was useful for evaluating system output clarity.

The developer also tested the system to try to invoke a failure of the rules. This brute force form of test provided insight into minor rule changes in addition to the standard system debugging. By the conclusion of this test, the developer should have a high level of understanding of the expertise encoded within the expert system.

3.2.4. *Prototype Consultation*

To run a sample consultation with FDES, the user must first run VP-Expert, set the path to the directory that contains FDES, load FISHWAY.KBS, select 'consult', and 'go'. Introductory screens display general information about the program, including nomenclature, then the questions presented in Appendix A are asked. Answers to these questions correspond to the design of a proposed fishway for the Hunt dam in southern Ontario. System responses were found to closely resemble the actual working design. Table I compares the results obtained by FDES and the actual proposed design for the Hunt dam.

4. Recommendations for Future Development

4.1. Summary

The problem which has been undertaken is a multi-disciplinary design problem that demands a combination of mathematical algorithms with heuristic, experience-based expertise. It is a difficult problem to approach with conventional programming because of the form of the knowledge and the need for future expansion of the encoded knowledge. ES concepts provide the programmer with an efficient approach to encode and access

TABLE I

Comparioson of FDES recommendation with the actual design for the Hunt Dam.

	Proposed design	FDES Recommendation
fishway type	vertical slot	vertical slot
design number	18	18
u/s invert	232.7	232.8 m
d/s invert	230.3 m	230.36 m
S_0	12.5%	13.36%
b_0	0.3 m	0.2 m
fishway ht	1.5 to 2.8 m	2.79 m

knowledge within a computer program environment.

FDES was developed to show that design problems can be successfully addressed by expert system techniques to help experienced designers and allow novice designers to produce good work in a reduced amount of time.

4.2. Recommendations

FDES demonstrates a fraction of the potential for intelligent decision support to be used in fishway design and water resource fields in general. Figure 2 depicts an ideal software package for fishway design. The determination of a fishway type recommendation is only an initial step.

Ideally, a preliminary ES would advise and instruct the user in gathering system data and the general problem approach. It would also have access to a flow estimation tool and a fish species recognition facility where an engineer could access help to determine local fish species and estimate their habits from previous experience.

Once a recommendation is found, the relevant design algorithms can be accessed to produce a configuration and dimension scaling for the recommended fishway type. This

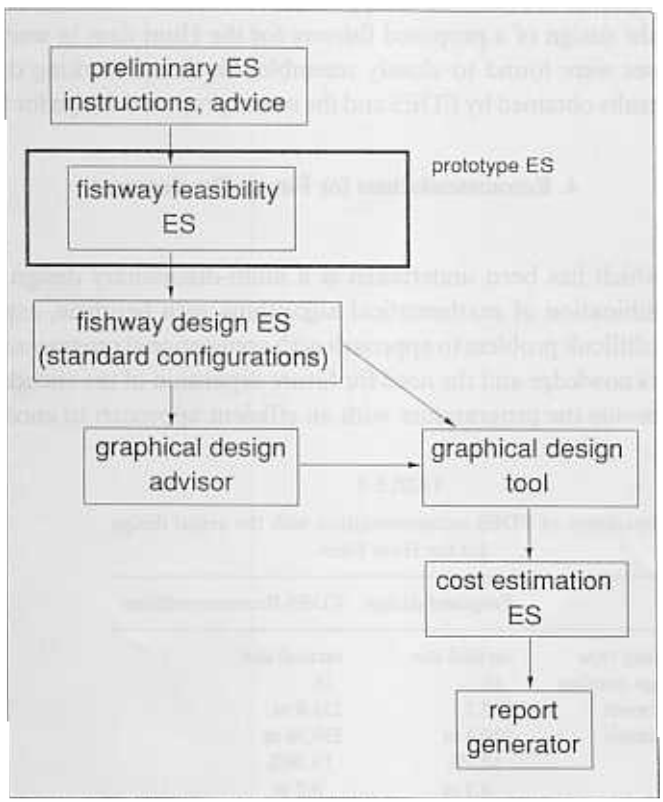

Fig. 2. Components of a fishway design expert system.

step is included in the prototype for vertical slot fishways only.

The next step in the support system would be to access a text and graphical library to show previous designs similar to the proposed design. This might help the designer to visualise the proposed design.

The most powerful extension to the fishway design ES is a specialized graphical drafting tool to produce drawings of a fishway using predefined fishway configurations and drawing them in two or three dimensions along a user specified path, automatically calculating elevations, resting pool spacing, etc.

After an initial design is generated, an additional ES would estimate construction costs based on similar previous designs. If the user is satisfied with the estimate, then a more detailed design and cost analysis can be started. Otherwise, the drafting tool could be used to generate another design option.

Finally, a report generator can use existing figures with drawings from the drafting tool and general text libraries to generate a skeleton report that can easily be modified to produce a standard quality report.

A support system like this could significantly reduce the time it takes to design a fishway and ensure a high level of consistency and design expertise.

Appendix A: FDES consultation

What are the months of the year that fish will pass through the fishway (MIGRATION PERIOD)?
April, May, June

Flows are estimated by plotting on log log paper the 3 day average flows from the period of record and fitting a straight line.

Using the Hw and Tw STAGE-DISCHARGE curves, elevations can be found corresponding to the design flows (NOTE: design flows only needed for the period of migration - shown below):
June
May
April
NOTE: for structures such as DAM SPILLWAYS, use the weir crest and the concrete spillway floor for the minimum elevations IF the minimum design flow is very low.

What is the MAX water level elevation at U/S side? (m)
234.4

What is the MIN water level elevation at U/S side? (m)
233.2

What is the MAX water level elevation at D/S side? (m)
232.9

What is the MIN water level elevation at D/S side? (m)
230.86

```
Does the fishway need to pass any of the following FISH SPECIES? (enter '?' for none)
walleye
```

(Walleye is selected from a large list of given fish species)

FISHWAY.KBS is now complete. System variables are passed to FTYPES.KBS and the consultation continues:

```
Locating fishway ENTRANCE and EXIT:          (PLAN VIEW)
                 |          |
      river      | u/s      |-\    EXIT       :
                 |          | |               : distance u/s
obstruction      \----------\|    fishway    :   :
                 |          | |                 : distance d/s
                 | d/s      |-/    ENTRANCE   :
Locations should be:
EXIT        set in some quiet area upstream of the obstruction
ENTRANCE    far enough downstream where stream velocities < 1.8 m/s

How far downstream of the obstruction is the fishway ENTRANCE (m)?
4

How far upstream of the obstruction is the fishway EXIT (m)?
2
```

```
Preliminary design boundary conditions:

The   min allowable fishway length      = 6 m
      max So                            = 39 %
      min fish length                   = 0.33 m
      max                               = 0.5 m
The water level range                   = 2.04 m

This data has been sent to 'OUTPUT' text file for further review.

Hit any key to continue.
```

The feasible types of fishways are:
vertical slot

The fishway type(s) recommended is (are):
vertical slot

Hit any key.

The vertical slot design is based on standard design number 18.

The invert elevations are as follows:
u/s = 232.8 m
d/s = 230.36 m

Other design information:
So = 13.36 %
bo = 0.20 m

The height of the fishway should be: 2.79 m
(including freeboard)

Hit any key to end consultation.

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