

# Habfuzz

A computational environment for data-driven, biologically-oriented  
environmental flow assessments



A quick user's guide

March 2017



### Contact Information

Hellenic Centre for Marine Research  
Institute of Marine Biological Resources and Inland Waters  
46.7 km Athens-Sounio ave.  
19013  
Anavyssos  
Greece  
Tel. +30 22910 76335  
Fax. +30 22910 76419  
Email. [ctheodor@hcmr.gr](mailto:ctheodor@hcmr.gr)  
URL. <http://www.hcmr.gr/en/>

National Technical University of Athens  
Department of Water Resources and Environmental Engineering  
Iroon Polytechniou 5  
15780  
Athens  
Greece  
Tel. +30 210 7722809  
Fax. +30 210 7722814  
Email. [stamou@central.ntua.gr](mailto:stamou@central.ntua.gr)  
URL. [https://www.hydro.ntua.gr/?set\\_language=en](https://www.hydro.ntua.gr/?set_language=en)

To report errors, bugs, possible amendments or anything else you would like to indicate, please contact Mr.  
Christos Theodoropoulos at [ctheodor@hcmr.gr](mailto:ctheodor@hcmr.gr)

TABLE OF CONTENTS

1. Overview..... 5

1.1. The fuzzy inference process..... 6

1.2. The fuzzy Bayesian inference process..... 9

2. Dependencies..... 10

3. Installing..... 10

3.1. Windows users..... 10

3.2. Linux users..... 10

3.3. Mac users..... 11

4. Usage..... 12

4.1. Input and output data..... 12

4.2. Running Habfuzz..... 14

4.2.1. The fuzzy inference process..... 14

4.2.2. The fuzzy Bayesian inference process..... 15

4.3. Modifying the code according to the user preferences..... 15

4.4. Cross validation..... 18

5. References..... 18

Appendix..... 19

## What's new on version 2.0?

- A. Habfuzz is now fully automated! Just input your data and get the results! No need for rule files. The software is data-driven and calculates everything it needs internally!
- B. Ten-fold cross validation is also internally applied to calculate model performance as the percentage of correctly classified instances.

## Why Habfuzz?

Habfuzz is a fully automated software, which calculates the instream habitat suitability by utilizing

1. The Mamdani - Assilian fuzzy inference process (Mamdani and Assilian, 1975) and
2. The Bayesian joint probability inference process as described in Brookes et al. (2010), with fuzzified inputs.

It is specifically structured to quickly calculate the fuzzy-logic- or fuzzy-Bayesian-based instream habitat suitability for fish or freshwater macroinvertebrates along a hydraulically simulated river reach. However, if appropriately modified, it can be applied to wider research topics requiring fuzzy logic to be addressed.

Instead of Habfuzz, you can use the non-free MATLAB Fuzzy Logic Toolbox (<http://www.mathworks.com/products/fuzzy-logic/>) or the free CASiMiR 2D software upon request ([http://www.casimir-software.de/ENG/habitate\\_eng.html](http://www.casimir-software.de/ENG/habitate_eng.html)). However, Habfuzz has been designed to be a one-click tool, for those researchers with no or very minor programming knowledge, in need of an easy-to-use software to calculate the habitat suitability along a hydrodynamically simulated river reach, based on fuzzy logic. For those researchers who can't afford to purchase MATLAB (because it does everything, but they only need a small amount of its capabilities). And for those self-studying researchers who need a very comprehensive, step-by-step, yet short tutorial to enable them quickly run a tool for a specific part of their project. Moreover, if you are planning to apply a fuzzy Bayesian inference process, Habfuzz is the only option available.

## 1. Overview

Let's suppose that you have a set of observations, which are microhabitat combinations of flow velocity (V), water depth (D) and substrate type (S) (Habfuzz requires temperature also but here we will only use three variables. Let's also suppose that you have successfully associated each of these combinations with the microhabitat suitability, either using freshwater fish, benthic invertebrates or any other biotic element of the aquatic ecosystem. You may now wonder which is the right method to enable you predict the habitat suitability of similar microhabitats based on your 'reference' combinations. And probably you have already excluded the Habitat Suitability Curves approach. Since it is very likely to conclude that fuzzy logic or Bayesian inference would be very appropriate, and assuming that scientifically you know what you are doing, this guide provides you with the technical help to implement one of these methods. A small example dataset (Table 1) is provided to ease the understanding of the software.

**Table 1.** Example dataset for this tutorial

Microhabitat	Flow velocity (m/s)	Water depth (m)	Substrate type
1	0.28	0.29	Boulders
2	0.05	0.08	Large stones
3	0.46	0.80	Small stones

## 1.1. The fuzzy inference process

(If you are already aware of these methods, proceed to section 2)

As initially proposed by Zadeh (1965) and described in detail by Ross (2010), the process of deriving the fuzzy-based habitat suitability, given the flow velocity, water depth and substrate type, can be summarized in four steps (Fig. 1):

### a. Fuzzification of the input variables

In this step, the user defines categories (membership functions) for each input variable and the input values of flow velocity, water depth and substrate type are assigned to one or more membership functions. By this procedure, crisp numerical values of each input variable are converted to a fuzzy 'degree of membership', ranging from 0 to 1 for each membership function. For example, a depth value of 14 cm may derive a membership degree of 0.7 for the 'shallow' membership function and 0.28 for the 'very shallow' membership function.

### b. Application of a fuzzy operator (AND or OR) in the antecedent (IF-THEN rules)

According to the reference data for the target aquatic community, the AND (min) or OR (max) operator is applied to each combination of variables (membership functions since step 1) and the derived value is assigned to the membership function of the output variable (defined in step 1), in this case the habitat suitability. For example, if the user defines five membership functions for habitat suitability (bad, poor, moderate, good, high), then the application of the fuzzy operator would result in

$$f_4(hs) = \min(f_2(D), f_3(V))$$

$$f_3(hs) = \min(f_3(D), f_2(V))$$

$$f_4(hs) = \min(f_2(D), f_4(V))$$

where,

$f_i$  denotes for the membership function of each input and output variable

$V$  is the flow velocity

$D$  is the water depth

$hs$  is the habitat suitability

etc., until all possible combinations of fuzzy inputs are assigned to an output membership function, based on the rationale that, for example,

*IF flow velocity is  $f_3$  (moderate) AND water depth is  $f_2$  (shallow) THEN habitat suitability is  $f_4$  (good).*

### c. Aggregation of outputs

In this step, the derived habitat suitability membership functions from each rule are combined into one fuzzy set. Usually, the OR (max) operator is applied to aggregate the same output fuzzy sets of the previous step. For example, the  $f_4(hs)$  is derived in the previous example two times by the IF-THEN rules. The final fuzzy set representing each habitat suitability class  $F_j$  would be

$$F_j = \max(f_i^1(hs), f_i^2(hs), \dots, f_i^v(hs))$$

d. *Defuzzification*

This final step is applied to derive one single habitat suitability value, by combining the membership degrees of all fuzzy habitat suitability classes. Among the various defuzzification methods, the 'centroid', 'maximum membership', 'weighted average' and 'mean-max membership methods' are described below.

i. *Centroid defuzzification*

Usually called the 'center of gravity' or 'center of area'. It can be defined by the algebraic expression

$$hs = \frac{\int xf(x)dx}{\int f(x)dx}$$

which can be numerically approximated by

$$hs = \frac{\sum_{i=1}^n x_i(f(x_i))}{\sum_{i=1}^n (f(x_i))}$$

where,

$f(x_i)$  is the membership degree at value  $x_i$

ii. *Maximum membership defuzzification*

This is the maximum membership degree observed by the aggregation step:

$$hs = \max(f(x))$$

iii. *Weighted average*

This method can be used only for symmetrical output membership functions and is calculated by weighting each output membership function by its largest membership degree:

$$hs = \frac{\sum_{i=1}^n \bar{x}_i(f(\bar{x}_i))}{\sum_{i=1}^n (f(\bar{x}_i))}$$

where,

$f(\bar{x}_i)$  is the membership degree at the average value  $\bar{x}_i$  of each membership function

iv. *Mean of maximum*

This method resembles the 'maximum membership' method. However, the maximum membership degree may not be unique but a range of degrees, from which the mean value is derived:

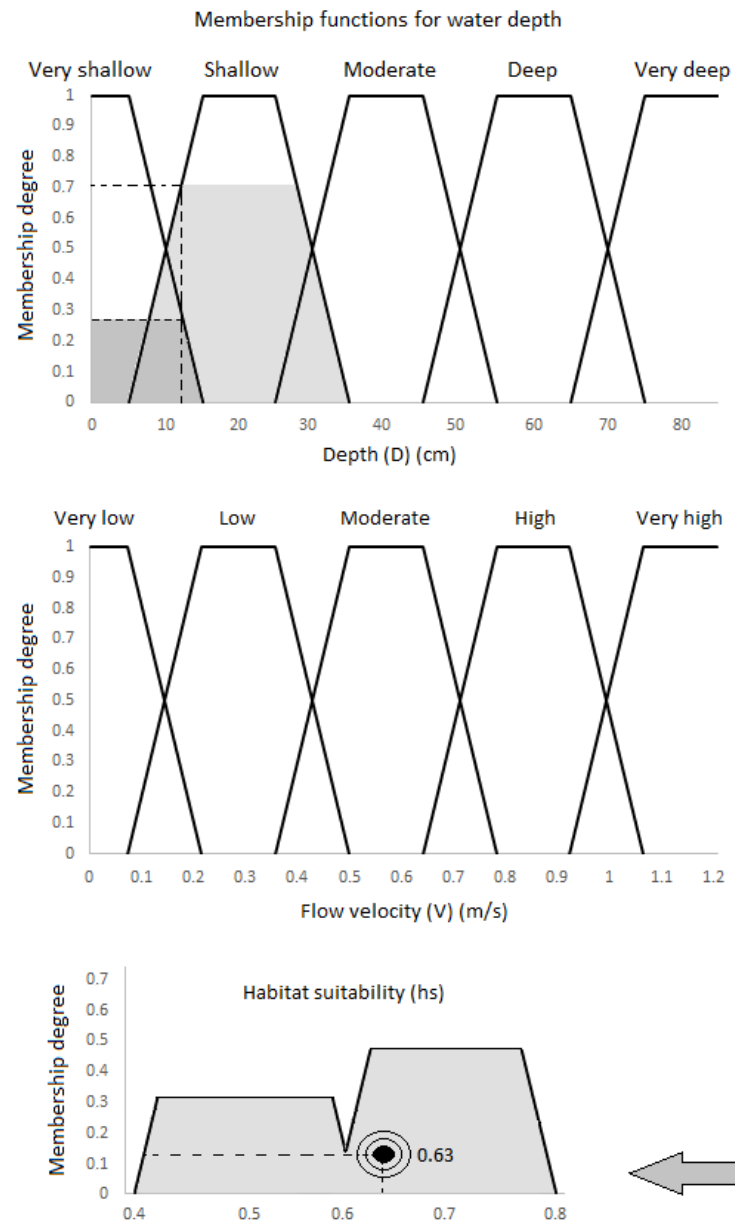
$$hs = \frac{x_a + x_b}{2}$$

where,

$x_a$  is the first value reaching the highest membership degree of the class with the highest membership and

$x_b$  is the last value with the highest membership degree of the class with the highest membership

## A. FUZZIFICATION



## B. FUZZY OPERATORS (IF - THEN RULES)

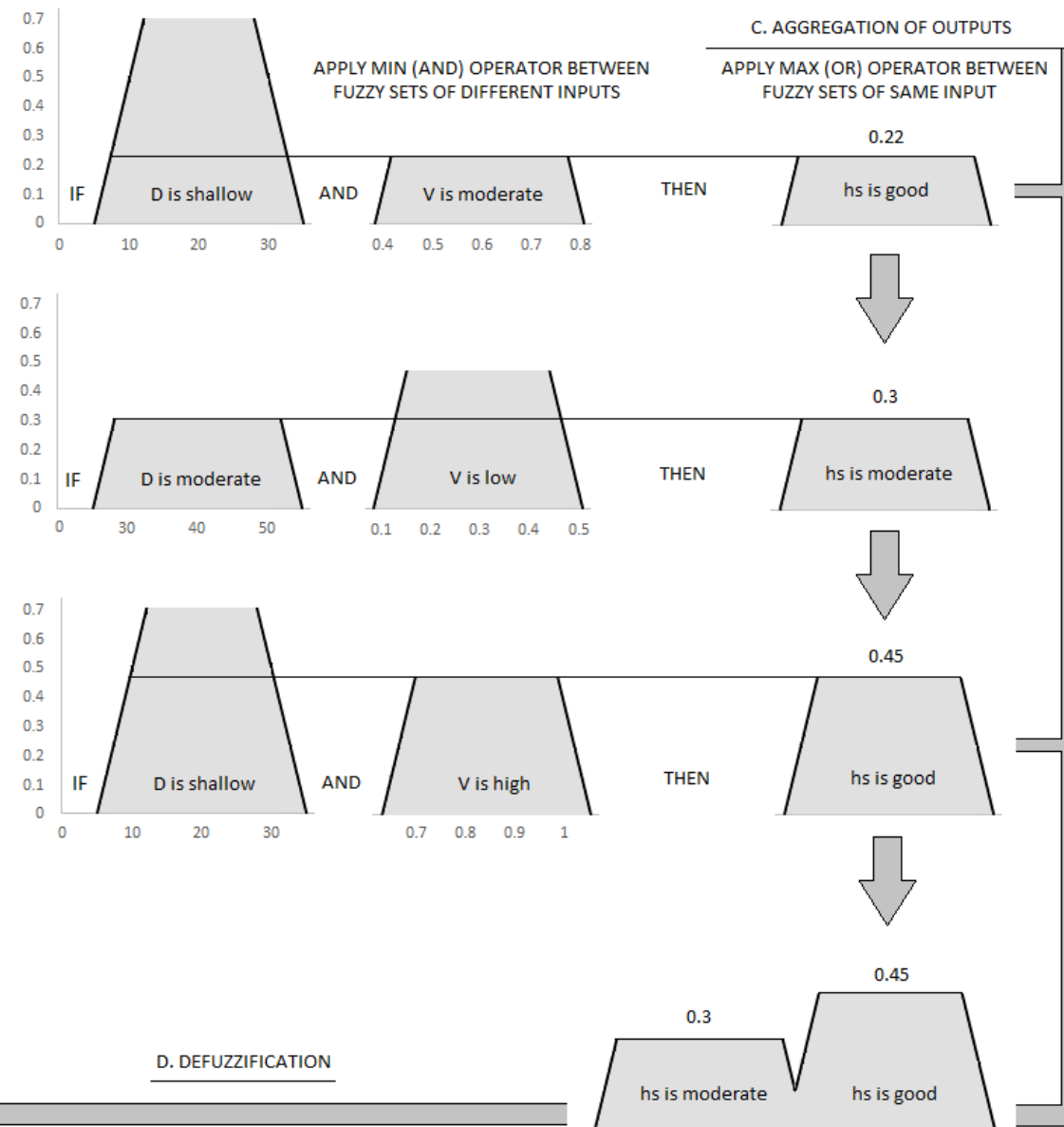


Figure 1. The fuzzy inference process



## 1.2. The fuzzy Bayesian inference process

The fuzzy Bayesian inference process utilizes the Bayesian joint probability and a classification system based on the 'expected utility' (briefly described Brookes et al., 2010) and can be summarized in three steps:

a. *Fuzzification of the input variables*

This step is the same as in the fuzzy inference process and results in the conversion of crisp numerical values to fuzzy 'degrees of membership', ranging from 0 to 1 for each membership function.

b. *Calculation of the Bayesian joint probability*

The joint probability for interdependent events is calculated as

$$P(A \cap B) = P(A|B)P(B) = P(B|A)P(A)$$

where,

$P(A \cap B)$  is the probability of event A and event B occurring together

$P(A|B)$  is the conditional probability of event A occurring given the event B occurred

$P(B|A)$  is the conditional probability of event B occurring given the event A occurred

In our case, flow velocity, depth and substrate type are considered independent of each other and the joint probability is calculated by replacing  $P(A|B)$  with  $P(A)$ . For example, the joint probability of the flow velocity being 0.5 m/s and the water depth being 0.2 m, given their probabilities  $P(V:0.5=0.8)$  and  $P(D:0.2=0.3)$  is  $0.8 \times 0.3 = 0.24$ . Habfuzz uses the fuzzified input values from step 1 as probabilities of occurrence of each input. For example, a crisp V values of 0.28 m/s corresponds to the 'moderate' fuzzy class by 0.2 degrees of membership and to the 'low' fuzzy class by 0.8. These values are used as the probabilities of occurrence of the 'moderate' and 'low' V classes.

c. *Classification of the outcome in habitat suitability classes*

Classification is applied by using the 'expected utility' equation, where in Habfuzz, habitat suitability is expressed as a score (bad - 0.1, poor - 0.3, moderate - 0.5, good - 0.7, high - 0.9) and multiplied by the joint probability of occurrence of each habitat suitability class (sum of probability\*score) as following:

$$EU(A) = \sum_{i=1}^n p(x_i|A)U(x_i)$$

where,

$EU(A)$  is the expected utility of action or event A

$P(x_i|A)$  is the probability of action or event A

$U(x_i)$  is a utility weight to convert a state to numerical values

## 2. Dependencies

- It is advised to install the GNU Fortran Compiler (download at <https://gcc.gnu.org/wiki/GFortranBinaries>) to quickly compile Habfuzz through the relevant Windows and OS X files (however, experienced users may also use their preferred compilers).
- For Mac users, Xcode (download at <https://developer.apple.com/xcode/>) with its relevant Command Line Tools should be installed to enable compiling through the GNU Fortran Compiler.

## 3. Installing

Habfuzz has been tested on Windows 10 - 32 bit and 64 bit operating systems, Ubuntu 16.04 and OS X 10.11 El Capitan (with Xcode 7.3.1 and Xcode 7.3.1. Command Line Tools), using the GNU Fortran Compiler. Depending on your operating system, follow the relevant instructions to run Habfuzz.

### 3.1. Windows users

An automated installer is available at <https://github.com/chtheodoro/habfuzz>, including the GNU Fortran Compiler.

If the user needs to modify the source code of Habfuzz, re-compilation is necessary. Using the GNU Fortran Compiler, you can either run the *wcompile.bat* file, or open a command window, navigate to the 'habfuzz' subfolder and type the relevant commands:

```
gfortran -c fdeclarations.f95
```

```
gfortran -o habfuzz habfuzz.f95 fdeclarations.f95 classifier.f95 combinations.f95 ruler.f95 fuzzifier.f95  
permutator.f95 rules2.f95 fuzzy.f95 fruler.f95 rules1.f95 centroid.f95 meanmax.f95 maxmem.f95 waver.f95  
randomizer.f95 iterator.f95 tester.f95 ftester.f95 performance.f95
```

```
del *.o
```

```
del *.mode
```

*habfuzz.exe* will then be replaced by the newly compiled one, being ready to run.

### 3.2. Linux users

Open the terminal and navigate to the 'habfuzz' subfolder. If you don't have the GNU Fortran Compiler, you need to be a root user (administrator) and type

```
sudo apt-get install gfortran
```

to install the compiler. Having gfortran installed, the commands necessary to compile are the following:

```
gfortran -c fdeclarations.f95
```

```
gfortran habfuzz.f95 fdeclarations.f95 classifier.f95 combinations.f95 ruler.f95 fuzzifier.f95 permutator.f95  
rules2.f95 fuzzy.f95 fruler.f95 rules1.f95 centroid.f95 meanmax.f95 maxmem.f95 waver.f95 randomizer.f95  
iterator.f95 tester.f95 ftester.f95 performance.f95 -o habfuzz
```

Be careful to write exactly the abovementioned commands, arranging the source files in the order given above. Then you can run habfuzz by typing:

```
./habfuzz
```

### **3.3. Mac OS X users**

You need to have Xcode installed together with the GNU Fortran Compiler and be a root user to enable compilation. Open the terminal and navigate to the 'habfuzz' subfolder. To compile, you can either run the *mcompile.sh* file (which automatically applies the compilation commands) by typing:

```
./mcompile.sh
```

or manually type the commands:

```
gfortran -c fdeclarations.f95
```

```
gfortran -o habfuzz fdeclarations.f95 habfuzz.f95 classifier.f95 combinations.f95 ruler.f95 fuzzifier.f95  
permutator.f95 rules2.f95 fuzzy.f95 fruler.f95 rules1.f95 centroid.f95 meanmax.f95 maxmem.f95 waver.f95  
randomizer.f95 iterator.f95 tester.f95 fttester.f95 performance.f95
```

Habfuzz can then be executed from the command line by typing

```
./habfuzz
```

## 4. Usage

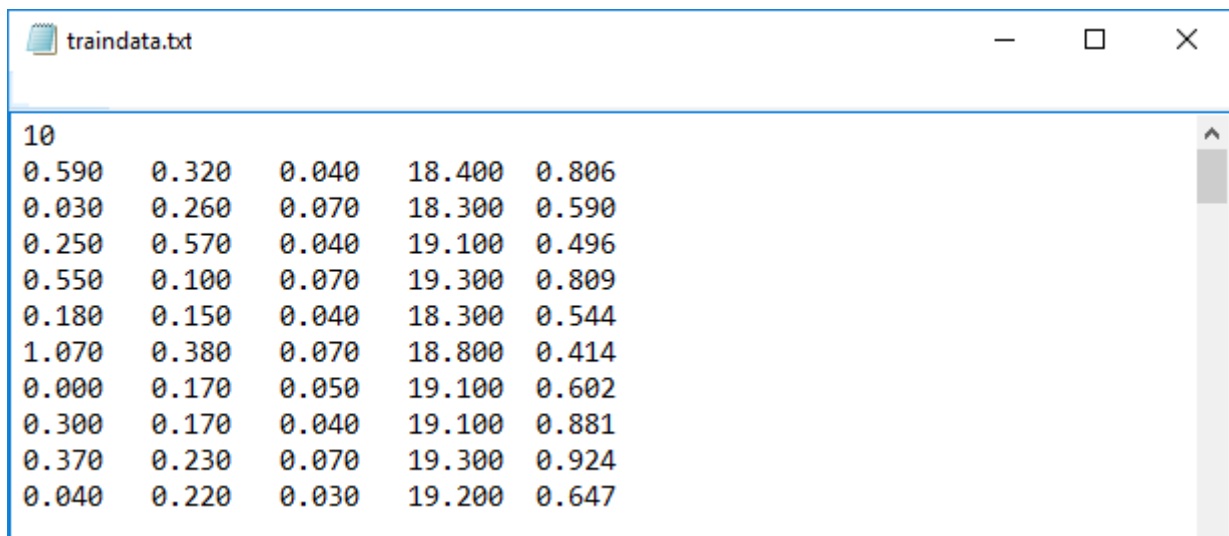
### 4.1. Input and output data

To run Habfuzz, you only need to prepare (i) a train-data file and (ii) test-data file. These files should be named *traindata.txt* and *testdata.txt* respectively and located at the same folder with *habfuzz.exe*.

#### 1. TRAINDATA.TXT

This file contains the data from which Habfuzz will be trained to predict.

The file should have five columns where V, D, S, T and hs are stored, respectively, for each microhabitat. Note that the first row should only contain one number describing the number of rows in the file (Fig. 2).

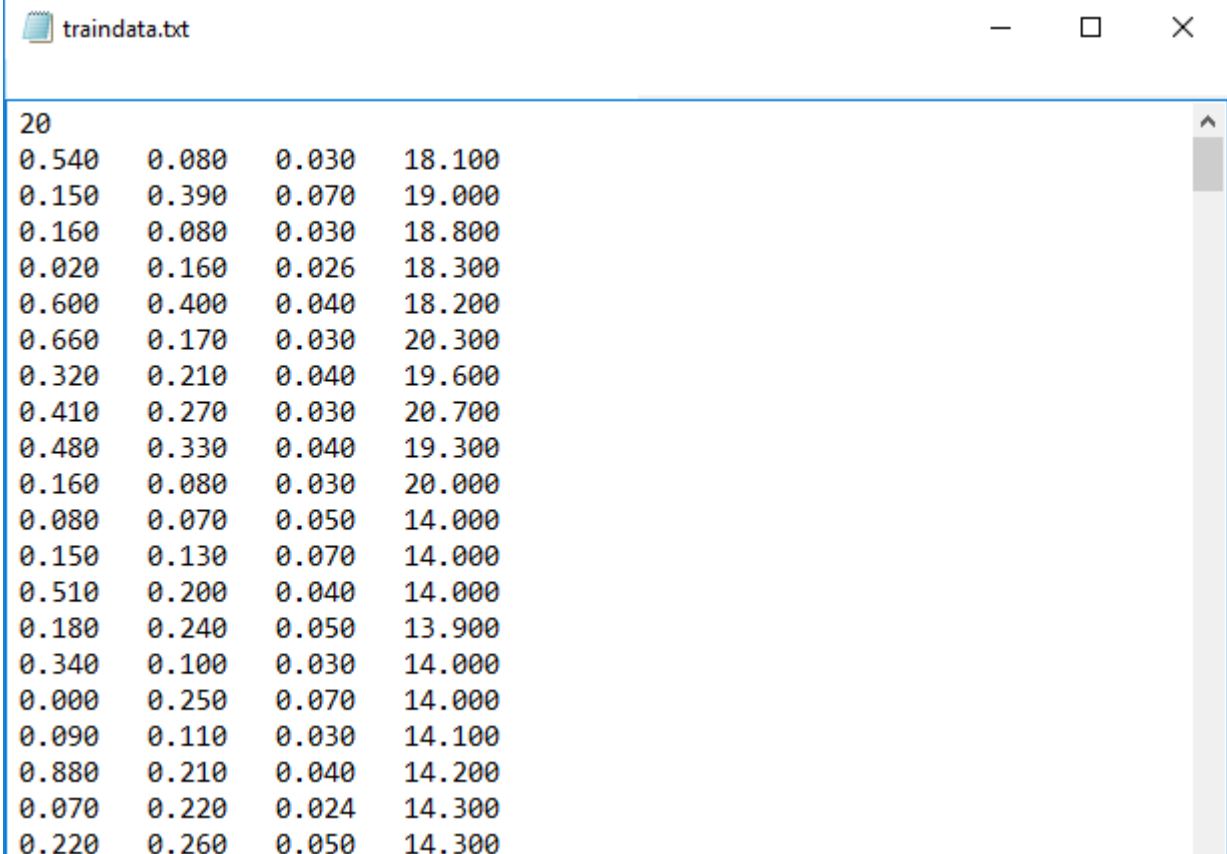


10				
0.590	0.320	0.040	18.400	0.806
0.030	0.260	0.070	18.300	0.590
0.250	0.570	0.040	19.100	0.496
0.550	0.100	0.070	19.300	0.809
0.180	0.150	0.040	18.300	0.544
1.070	0.380	0.070	18.800	0.414
0.000	0.170	0.050	19.100	0.602
0.300	0.170	0.040	19.100	0.881
0.370	0.230	0.070	19.300	0.924
0.040	0.220	0.030	19.200	0.647

Figure 2. *traindata.txt* example

#### 2. TESTDATA.TXT

This file contains the data with unknown habitat suitability, which is going to be predicted by Habfuzz based on the train data. This file should have the same format as the *traindata.txt* but without the hs column (Fig. 3).



The screenshot shows a text editor window titled 'traindata.txt'. It contains a table with 20 rows and 4 columns of numerical data. The first row is a header with the number '20'. The subsequent 19 rows contain four numerical values each, separated by spaces. The values are: 0.540, 0.080, 0.030, 18.100; 0.150, 0.390, 0.070, 19.000; 0.160, 0.080, 0.030, 18.800; 0.020, 0.160, 0.026, 18.300; 0.600, 0.400, 0.040, 18.200; 0.660, 0.170, 0.030, 20.300; 0.320, 0.210, 0.040, 19.600; 0.410, 0.270, 0.030, 20.700; 0.480, 0.330, 0.040, 19.300; 0.160, 0.080, 0.030, 20.000; 0.080, 0.070, 0.050, 14.000; 0.150, 0.130, 0.070, 14.000; 0.510, 0.200, 0.040, 14.000; 0.180, 0.240, 0.050, 13.900; 0.340, 0.100, 0.030, 14.000; 0.000, 0.250, 0.070, 14.000; 0.090, 0.110, 0.030, 14.100; 0.880, 0.210, 0.040, 14.200; 0.070, 0.220, 0.024, 14.300; 0.220, 0.260, 0.050, 14.300.

traindata.txt			
20			
0.540	0.080	0.030	18.100
0.150	0.390	0.070	19.000
0.160	0.080	0.030	18.800
0.020	0.160	0.026	18.300
0.600	0.400	0.040	18.200
0.660	0.170	0.030	20.300
0.320	0.210	0.040	19.600
0.410	0.270	0.030	20.700
0.480	0.330	0.040	19.300
0.160	0.080	0.030	20.000
0.080	0.070	0.050	14.000
0.150	0.130	0.070	14.000
0.510	0.200	0.040	14.000
0.180	0.240	0.050	13.900
0.340	0.100	0.030	14.000
0.000	0.250	0.070	14.000
0.090	0.110	0.030	14.100
0.880	0.210	0.040	14.200
0.070	0.220	0.024	14.300
0.220	0.260	0.050	14.300

Figure 3. *testdata.txt* example

The output of Habfuzz is a file named *suitability.txt* containing a single column with all the predicted habitat suitabilities (ranging from 0 - unsuitable to 1 - suitable) calculated for each input element (node) in the same order as with the input files and a *log.txt* file with the internal parameters of the prediction process. Both files are placed by the program in the 'habfuzz' subfolder.

During the fuzzy inference process, habitat suitability is initially a combination of fuzzy membership functions (five classes of habitat suitability - bad, poor, moderate, good, high) and through the defuzzification process it is converted into a crisp output ranging from 0 to 1. The inputs and the output suitability of Habfuzz are depicted in Fig. 1. In the fuzzy Bayesian inference process, habitat suitability is expressed using the same five classes. Each class is assigned with a utility score (bad - 0.1, poor - 0.3, moderate - 0.5, good - 0.7, high - 0.9) and multiplied by the joint probability of each combination observed

Table 2. Manning's n for various substrate types applied in Habfuzz

Bed material	Size (diameter)	Manning's n
Boulders	>25 cm	0.070
Large stones	12-25 cm	0.050
Small stones	6-12 cm	0.040
Large gravel	2-6 cm	0.030
Medium gravel	0.6-2 cm	0.026
Fine gravel	0.2-0.6 cm	0.024
Sand	<0.2 cm	0.022
Silt	-	0.020

## 4.2. Running Habfuzz

(using the example dataset of table 1)

After having the input files ready run the program. The command prompt opens and after a short welcome message the software asks for the inference process to be implemented (Fig. 3).

```

ee  ee  eeeee  eeeee  eeeee  ee  ee  eeeee  eeeee
ee  ee  ee  ee  ee  ee  ee  ee  ee  ee  ee
eeeeeee eeeeeeee eeeee  eeeee  ee  ee  ee  ee
eeeeeee eeeeeeee eeeee  eeeee  ee  ee  ee  ee
ee  ee  ee  ee  ee  ee  ee  ee  ee  ee  ee
ee  ee  ee  ee  eeeee  ee  eeeee  eeeee  eeeee

Habfuzz+ 2.0

Fuzzy logic and fuzzy Bayesian inference for the calculation
of the instream hydraulic habitat suitability

Fully automated with 10-fold cross-validation capability
Just provide your input data matrix and get the resulting suitability

Press ENTER to start

Select modelling method
1: Fuzzy logic
2: Fuzzy Bayesian inference
```

Figure 3. Selection of the inference process in Habfuzz

### 4.2.1. The fuzzy inference process

If the Fuzzy inference process is selected, the program prompts the user to select the desired management scenario to implement (Fig. 4). There are three available scenarios based on the method used for deriving the outcome of each IF-THEN rule from the reference conditions of the program, (i) the average scenario, where the different suitability values for the same combinations of flow velocity, water depth and substrate type are averaged to derive the final habitat suitability, (ii) the worst scenario, where the final suitability is derived from the minimum observed suitability and (iii) the optimum scenario where the final suitability is derived by the maximum observed suitability. A default scenario is also present (the moderate scenario). Note that if a specific combination in the observed data does not match a combination in the reference data, the program returns a value of '-1' for the habitat suitability.

After selecting the desired scenario, the user is asked to select the defuzzification method (see section 1). A default method (centroid) is available. After selecting the defuzzification method, Habfuzz calls the relevant subroutines to perform the tasks selected. The program informs the user when the process is completed and indicates the *suitability.txt* file created where the suitability values are stored and the *log.txt* file with the fuzzy membership degrees for each class. Both files are located in the 'habfuzz' subfolder.

```

Select the preferred scenario to implement
1: Average
2: Worst
3: Optimum
4: Default
1

Select the preferred defuzzification method
1: Centroid
2: Max membership
3: Weighted average
4: Mean-max membership
5: Default
```

Figure 4. The 'fuzzy' option of Habfuzz

Using the example data of table 1, the crisp input values for V and D, are fuzzified as depicted in table 3.

**Table 3.** Fuzzification results for the example dataset. Different microhabitat are shaded differently.

Crisp inputs	Fuzzy membership classes						
	V Very Low	V Low	V Moderate	D Very Shallow	D Shallow	D Moderate	D Very Deep
V = 0.28	0	0.8	0.2				
V = 0.05	1	0	0				
V = 0.46	0	0	1				
D = 0.29				0	0.333	0.667	0
D = 0.08				0.333	0.667	0	0
D = 0.80				0	0	0	1

V, Flow Velocity; D, Water Depth

Habfuzz then checks each combination of inputs (their fuzzified values) and assigns a membership degree using the AND (min) operator to the relevant habitat suitability class they belong according to the IF-THEN rules written in *smod.f95*, *swors.f95* and *sopt.f95* and depending on the selected management scenario. Let's assume that the user has chosen the moderate scenario. The membership of each combination to the suitability classes (including the substrate type) is depicted in table 4.

**Table 4.** Checking the relevant IF-THEN rules and assigning membership degrees to the suitability class by applying the AND (min) operator. Different shading denotes the different microhabitats after fuzzification.

V	D	S	Habitat Suitability
Moderate (0.2)	Moderate (0.667)	Boulders (1)	-
Moderate (0.2)	Shallow (0.333)	Boulders (1)	High (0.2)
Low (0.8)	Moderate (0.667)	Boulders (1)	Moderate (0.667)
Low (0.8)	Shallow (0.333)	Boulders (1)	Good (0.333)
Very Low (1)	Very Shallow (0.667)	Large stones (1)	Good (0.667)
Very Low (1)	Shallow (0.333)	Large stones (1)	Good (0.333)
Moderate (1)	Very Deep (1)	Small stones (1)	-

V, Flow Velocity; D, Water Depth; S, Substrate type

Habfuzz then combines the same habitat suitability classes observed (aggregation step) using the OR (max) operator and the different membership degrees of all classes observed are defuzzified using one of the methods described in section 1. The results of the aggregation and defuzzification processes (in this case we have chosen the centroid defuzzification method) are depicted in table 5.

**Table 5.** Aggregation of outputs using the OR (max) operator. It can be seen that microhabitat 3 is not referred in the IF-THEN rules and a value of -1 is returned by Habfuzz.

Microhabitat	V	D	S	Habitat suitability
1	0.28	0.29	Boulders	0.622
2	0.05	0.08	Large stones	0.700
3	0.46	0.80	Small stones	-1

V, Flow Velocity; D, Water Depth; S, Substrate type

#### 4.2.2. The fuzzy Bayesian inference process

If the fuzzy Bayesian process is selected, the program immediately calculates the habitat suitability according to the steps described previously and outputs two .txt files, the *suitability.txt* and the *log.txt* with the same contents as in the fuzzy inference process.

Again, using the example data of table 1, the crisp input values for V and D, are fuzzified as depicted in table 3. The process then treats the fuzzified membership degrees as the probability of each observation occurring, suggesting for example that *‘the probability of habitat suitability being high is the joint probability that V is moderate, D is shallow and S is boulders’*. In the example dataset, this concept is depicted for each microhabitat in tables 6, 7 and 8.

**Table 6.** (A) The joint probability table for the fuzzified inputs of microhabitat 1 (S=Boulders, not shown but included). (B) Joint probability after including the probability of the habitat suitability (not shown) class for each combination.

(A) Microhabitat 1		D (P)		JP = P(V) x P(D) x P(S) Substrate's P is always 1 since S is not fuzzified.
V (P)		Shallow (0.333)	Moderate (0.667)	
Low (0.8)		0.2664	0.5336	
Moderate (0.2)		0.0666	0.1334	

(B) Microhabitat 1		D (P)						JP = P(V) x P(D) x P(S) x P(HS)
V (P)		Shallow (0.333)				Moderate (0.667)		
Low (0.8)		0.1455	0.0729	0.0239	0.0239	0.2668	0.2668	
Moderate (0.2)		0.0667				-		

V, Flow Velocity; D, Water Depth; S, Substrate type; JP, Joint probability; HS, Habitat Suitability; Blue colour, High HS; Green colour, Good HS; Yellow colour, Moderate HS; Red, Bad HS

**Table 7.** (A) The joint probability table for the fuzzified inputs of microhabitat 2 (S=Large stones, not shown but included). (B) Joint probability after including the probability of the habitat suitability class for each combination. JP: Joint probability.

(A) Microhabitat 2		D (P)		JP = P(V) x P(D) x P(S)
V (P)		Very Shallow (0.667)	Shallow (0.333)	
Low (1)		0.667	0.333	

(B) Microhabitat 2	D (P)							Joint Probability = P(V) x P(D) x P(S) x P(HS)
V (P)	Very Shallow (0.667)			Shallow (0.333)				
Very Low (1)	0.1667	0.3335	0.1667	0.0639	0.1412	0.1022	0.0256	

V, Flow Velocity; D, Water Depth; S, Substrate type; JP, Joint probability; HS, Habitat suitability; Blue colour, High suitability; Green colour, Good suitability; Yellow, Moderate suitability; Orange, Poor suitability

**Table 8.** The joint probability table for the fuzzified inputs of microhabitat 2 (S=Small stones, not shown but included). Since the specific combination is not present in the *rules.f95* file, no further calculations are applied.

Microhabitat 3		D (P)		Joint Probability = P(V) x P(D) x P(S)
V (P)		Very Deep (1)		
Moderate (1)		1		

V, Flow Velocity; D, Water Depth; S, Substrate type; JP, Joint probability

Habfuzz then assigns a score at each habitat suitability class to calculate the final suitability output (bad - 0.1, poor - 0.3, moderate - 0.5, good - 0.7, high - 0.9), using the ‘expected utility’ equation. Each probability from tables 6B and 7B is multiplied by the score of each relevant suitability class and all products are summed (for each microhabitat) to derive the final habitat suitability. The results of the fuzzy Bayesian inference process are presented in table 9.

**Table 9.** The fuzzy Bayesian calculation of habitat suitability using the ‘expected utility (EU)’ equation

Microhabitats	Joins probability combinations							EU
1 -->	0.1455 x 0.9	0.0729 x 0.7	0.0239 x 0.5	0.0239 x 0.1	0.2668 x 0.7	0.2668 x 0.5	0.0667 x 0.9	0.577
2 -->	0.1667 x 0.9	0.3335 x 0.7	0.1667 x 0.5	0.0639 x 0.9	0.1412 x 0.7	0.1022 x 0.5	0.0256 x 0.3	0.677



### 4.3. Modifying the code according to the user preferences

While the software is developed to quickly apply the fuzzy and fuzzy Bayesian inference processes for the calculation of the habitat suitability, the user can change the code according to his/her requirements in order to input his/her reference data or to apply the processes for other topics requiring the implementation of fuzzy logic. It is advised to perform the unit tests available in the 'tests' subfolder after each modification to ensure the program is properly working. Modifications can be applied at specific Habfuzz files and variables mentioned below:

1. INPUT ARRAY SIZE - The current limit of input array size (the number of rows at each file and therefore the number of nodes in the computational grid) has been set at 3000. However, the user can change this value by changing accordingly the 'rsize' parameter in the *fdeclarations.f95* file.
2. CLASSIFICATION and FUZZIFICATION - The classification and fuzzification processes of Habfuzz are included in the subroutines *classifier.f95* and *fuzzifier.f95*, respectively. The *classifier.f95* classifies the input data into the classes mentioned above (5 classes for V, 5 classes for D, 8 classes for S and 5 classes for T and 5 classes for hs). The *fuzzifier.f95* converts the crisp inputs of flow velocity and water depth to fuzzy sets (membership functions). The subroutine creates 5 classes for each of the variables V, D, and T. S is treated as an eight-class crisp input throughout the process since the types of substrate are well defined and there is no need to be fuzzified. The user can either change the values at each membership function included in the *fdeclarations.f95* file (Fig. 5), which results in changing the trapezoidal vertices of each membership function or change the whole membership function.

```
!-----!  
!Trapezoidal-shaped membership functions for flow velocity (V), water depth (D), temperature (T) !  
!-----!  
!FLOW VELOCITY!  
real, parameter :: uvla = 0.05, uvlb = 0.10 !VERY LOW V class!  
real, parameter :: ula = 0.05, ulb = 0.10, ulc = 0.15, uld = 0.20 !LOW V class!  
real, parameter :: uma = 0.15, umb = 0.20, umc = 0.40, umd = 0.50 !MODERATE V class!  
real, parameter :: uha = 0.40, uhb = 0.50, uhc = 0.70, uhd = 0.80 !HIGH V class!  
real, parameter :: uvha = 0.7, uvhb = 0.80 !VERY HIGH V class!  
!-----!  
!WATER DEPTH!  
real, parameter :: dvla = 0.10, dvlb = 0.15 !The VERY SHALLOW D class!  
real, parameter :: dla = 0.15, dlb = 0.20, dlc = 0.30, dld = 0.35 !The SHALLOW D class!  
real, parameter :: dma = 0.30, dmb = 0.35, dmc = 0.55, dmd = 0.60 !The MODERATE D class!  
real, parameter :: dda = 0.55, ddb = 0.60, ddc = 0.70, ddd = 0.75 !The DEEP D class!  
real, parameter :: dvda = 0.75, dvdb = 0.80 !The VERY DEEP D class!  
!-----!  
!TEMPERATURE!  
real, parameter :: tvla = 13, tvlb = 14 !The VERY LOW T class!  
real, parameter :: tla = 13, tlb = 14, tlc = 18, tld = 19 !The LOW T class!  
real, parameter :: tma = 18, tmb = 19, tmc = 23, tmd = 24 !The MODERATE T class!  
real, parameter :: tha = 23, thb = 24, thc = 28, thd = 29 !The HIGH T class!  
real, parameter :: tvha = 28, tvhb = 29 !The VERY HIGH T class!  
!-----!
```

Figure 5. The trapezoidal-shaped membership functions (*fdeclarations.f95*)

It is not advised to make any changes in the 'defuzzification' subroutines as they do not depend on the array size of other files and they don't require any changes to work properly even if the abovementioned modifications are applied. Still, an experienced FORTRAN user can modify the defuzzification subroutines according to his/her needs. After each modification in the files of Habfuzz, re-compilation is necessary as described in section 3.

#### 4.4. Cross validation

Habfuzz applies a 10-fold cross validation algorithm to calculate the performance of the model based on the training dataset, deriving the correctly classified instances (CCI) as the microhabitats where the calculated habitat suitability class is the same as the one provided by the user in the *traindata.txt* file.

### 5. References

Brookes C.J., Kumar V. and Lane S.N. 2010. A comparison of Fuzzy, Bayesian and Weighted Average formulations of an in-stream habitat suitability model. Proceedings of the International Congress on Environmental Modelling and Software, 5-8 Jul 2010, Ottawa, Canada. Available at <http://www.iemss.org/iemss2010/papers/S20/S.20.07.Model%20selection%20and%20uncertainty%20A%20comparison%20of%20Fuzzy,%20Bayesian%20and%20Weighted%20Average%20formulations%20of%20an%20instream%20habitat%20suitability%20model%20-%20CHRISTOPHER%20BROOKES.pdf>

Mamdani E.H. and Assilian S. 1975. An experiment in linguistic synthesis with a fuzzy logic Controller. International Journal of Man-Machine Studies 7: 1-13.

Ross T.J. 2010. Fuzzy logic with engineering applications. Third Edition, John Wiley and Sons, UK.

Zadeh L.A. 1965. Fuzzy sets. Information and Control 8: 338–353.

## APPENDIX

Manning's n for channels (Chow, 1959)

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
<b>1. Main Channels</b>			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
<b>2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages</b>			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
<b>3. Floodplains</b>			
a. Pasture, no brush			
1. short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. dense willows, summer, straight	0.110	0.150	0.200

2. cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. same as 4. with flood stage reaching branches	0.100	0.120	0.160
<b>4. Excavated or Dredged Channels</b>			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.020
2. clean, after weathering	0.018	0.022	0.025
3. gravel, uniform section, clean	0.022	0.025	0.030
4. with short grass, few weeds	0.022	0.027	0.033
b. Earth winding and sluggish			
1. no vegetation	0.023	0.025	0.030
2. grass, some weeds	0.025	0.030	0.033
3. dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. earth bottom and rubble sides	0.028	0.030	0.035
5. stony bottom and weedy banks	0.025	0.035	0.040
6. cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. no vegetation	0.025	0.028	0.033
2. light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. smooth and uniform	0.025	0.035	0.040
2. jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. dense weeds, high as flow depth	0.050	0.080	0.120
2. clean bottom, brush on sides	0.040	0.050	0.080
3. same as above, highest stage of flow	0.045	0.070	0.110
4. dense brush, high stage	0.080	0.100	0.140
<b>5. Lined or Constructed Channels</b>			
a. Cement			
1. neat surface	0.010	0.011	0.013
2. mortar	0.011	0.013	0.015
b. Wood			
1. planed, untreated	0.010	0.012	0.014
2. planed, creosoted	0.011	0.012	0.015
3. unplanned	0.011	0.013	0.015
4. plank with battens	0.012	0.015	0.018
5. lined with roofing paper	0.010	0.014	0.017

c. Concrete			
1. trowel finish	0.011	0.013	0.015
2. float finish	0.013	0.015	0.016
3. finished, with gravel on bottom	0.015	0.017	0.020
4. unfinished	0.014	0.017	0.020
5. gunite, good section	0.016	0.019	0.023
6. gunite, wavy section	0.018	0.022	0.025
7. on good excavated rock	0.017	0.020	
8. on irregular excavated rock	0.022	0.027	
d. Concrete bottom float finish with sides of:			
1. dressed stone in mortar	0.015	0.017	0.020
2. random stone in mortar	0.017	0.020	0.024
3. cement rubble masonry, plastered	0.016	0.020	0.024
4. cement rubble masonry	0.020	0.025	0.030
5. dry rubble or riprap	0.020	0.030	0.035
e. Gravel bottom with sides of:			
1. formed concrete	0.017	0.020	0.025
2. random stone mortar	0.020	0.023	0.026
3. dry rubble or riprap	0.023	0.033	0.036
f. Brick			
1. glazed	0.011	0.013	0.015
2. in cement mortar	0.012	0.015	0.018
g. Masonry			
1. cemented rubble	0.017	0.025	0.030
2. dry rubble	0.023	0.032	0.035
h. Dressed ashlar/stone paving	0.013	0.015	0.017
i. Asphalt			
1. smooth	0.013	0.013	
2. rough	0.016	0.016	
j. Vegetal lining	0.030		0.500