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Mathematical model on simulating fish-behavior in river flows

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«COMPUTATIONAL MECHANICS»

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ABSTRACT

The main research questions the present dissertation attempts to address are: (1) how can someone analyze and simulate fish movement and fish behavior in a river flow and (2) how can the above behavior be modeled by structuring a mathematical model describing the main aspects of fish behavior-movement. By addressing the above research questions, researchers will be able to create hydraulic structures such as fish passes, so that fish can recognize and orient themselves towards them. The present work attempts to address the fore-mentioned research questions by structuring a mathematical model for simulating fish behavior in river flows. In particular, (1) a background research review on fish behavior in rivers, stimuli that affect the decision making while swimming, movement related to each behavior decision and already existing behavior models was conducted, (2) a fish behavior mathematical model was structured based on existing fish behavior models, and (3) an implementation of the model was conducted on a river in the Jedsted area of Denmark, where fish movement data were recorded, in the scope of validating the model that was created. Hydrodynamic stimuli for fish behavior is calculated with the use of existing Computational Fluid Dynamics (CFD) models, and TELEMAC-2D in particular. In the model created, flow velocities and acceleration magnitude are used as stimuli to determine different behavior decisions and related movement. For the present model three different behavior responses were modeled: B1, to swim along with the flow, which consists of a Biased Correlated Random Walk in the direction of the flow, B2, to swim towards regions of faster flows thus facilitating downstream migration through obstacle avoidance, B3, to swim against flow vector, which is an escape response, where fish abandons downstream migration to swim upstream. The model also applies a random change in swimming depth, incorporated in the above behavior responses. Acceleration magnitude is the triggering stimuli to activate different behaviors and flow velocities can influence its trajectory

Keywords: Fish behavior modelling, Fish Passes, ecological modeling

ΕΚΤΕΤΑΜΕΝΗ ΠΕΡΙΛΗΨΗ

Σκοπός της παρούσας εργασίας

Ο κύριος σκοπός της παρούσας εργασίας είναι η δόμηση ενός μαθηματικού μοντέλου συμπεριφοράς ιχθύων, ικανού να προσομοιώσει τη συμπεριφορά ιχθύων στην ανάντη περιοχή ενός Υδροηλεκτρικού Έργου (ΥΗΕ), αξιοποιώντας ερεθίσματα που δέχονται από το περιβάλλον ρευστό. Η επίτευξη του στόχου αυτού έγινε αξιοποιώντας δεδομένα προηγούμενης μεταπτυχιακής διατριβής, όπου αναλύθηκε η λειτουργία υπάρχοντος μοντέλου συμπεριφοράς ιχθύων. Αξιοποιώντας βασικές λειτουργίες του υπάρχοντος μοντέλου, καθώς και τη διαθέσιμη βιβλιογραφία δομήθηκε μαθηματικό / υπολογιστικό μοντέλο, που ανταποκρίνεται στη συμπεριφορά ιχθύων του ευρωπαϊκού χώρου. Η δόμηση του παρόντος μοντέλου αποτελεί καινοτομία, δεδομένου της ύπαρξης λίγων μόνο αντίστοιχων μοντέλων, και αναμένεται να συνεισφέρει σημαντικά στην κατανόηση της συμπεριφοράς ιχθύων και στη μελέτη ΥΗΕ του ελλαδικού χώρου, με σκοπό την προστασία των ιχθύων.

Μεθοδολογία και μέρη της εργασίας

1 ΕΙΣΑΓΩΓΗ

Η κατασκευή υδραυλικών έργων σε ποτάμια αν και έχει μεγάλη σημασία για τη οικονομία μιας χώρας, επιφέρει συνέπειες, διακόπτοντας τη φυσική ροή των ποταμών και δημιουργώντας ένα τεχνητό εμπόδιο, το οποίο οι ιχθύες αδυνατούν να υπερβούν κατά τη μετανάστευση τους προς τα ανάντη ή τα κατάντη. Αναγνωρίζοντας τις περιβαλλοντικές επιπτώσεις των υδραυλικών έργων, η Ευρωπαϊκή Ένωση εισήγαγε οδηγία-πλαίσιο {8}, σύμφωνα με την οποία τα υδάτινα σώματα απαιτείται να διατηρούν μια καλή οικολογική κατάσταση**.** Βασική προϋπόθεση αυτού είναι η απρόσκοπτη διέλευση ιχθύων προς τα ανάντη και κατάντη του ποταμού {15}, το οποίο απαιτεί ορθή χωροθέτηση των υδραυλικών έργων. Στο παραπάνω αναμένεται να συνδράμει η κατανόηση της κίνησης των ιχθύων στα ποτάμια με βάση τα υδροδυναμικά χαρακτηριστικά του πεδίου ροής.
Η κίνηση των ιχθύων μπορεί να γίνει, υπό το πρίσμα της μελέτης της συμπεριφοράς τους, καθώς προσανατολίζονται και ταξιδεύουν σε μεγάλο βαθμό όπως και οι άνθρωποι {23}. Προς αυτή την κατεύθυνση έχουν αναπτυχθεί ένα αριθμός μαθηματικών μοντέλων προσομοίωσης της κίνησης ιχθύων με βάση τη συμπεριφορά τους {1}, {12}, {13}, {14}, {15}, {3}, ενώ έχει γίνει και εκτενής βιβλιογραφική ανασκόπηση και μελέτη ευαισθησίας σε ορισμένα από αυτά {11}.
Στη βιβλιογραφία υπάρχει πληθώρα ερευνών σχετικά με τον τρόπο που αντιλαμβάνονται και αντιδρούν οι ιχθύες στα υδροδυναμικά χαρακτηριστικά του πεδίου ροής με βάση τη συμπεριφορά τους. Οι ιχθύες αντιλαμβάνονται τα υδροδυναμικά χαρακτηριστικά της ροής, όπως ταχύτητες και επιταχύνσεις, και διαμορφώνουν την εικόνα του περιβάλλοντος χώρου τους {5}. Το παραπάνω γίνεται εντός μιας περιοχής αντίληψης, η οποία εκτείνεται σε μέγιστη απόσταση ίση με δύο μήκη ιχθύος {4}. Η περιοχή αντίληψης μπορεί να είναι κυκλική ή παραμορφωμένη {12}.
Έρευνες σχετικά με τις ταχύτητες κολύμβησης των ιχθύων έδειξαν ότι εμφανίζονται τρείς βασικές κατηγορίες κολύμβησης: (1) Συνεχής κολύμβηση, (2) παρατεταμένη κολύμβηση, και (3) εκρηκτική κολύμβηση {26} και συνδέονται με αντίστοιχες συμπεριφορές. Σχετικές έρευνες παρουσιάζουν ορισμένες βασικές συμπεριφορές κολύμβησης ως προς τη ροή {25}, {13}: (1) Ενεργή κολύμβηση στην κατεύθυνση της ροής, (2) παθητική κολύμβηση και συμπαράσυρση από τη ροή, (3) αποφυγή και μεταβολή γωνίας σε σχέση με την ροή, και (4) διαφυγή και κολύμβηση αντίθετα στη ροή.
Κατά τη διάρκεια της μετανάστευσης προς τα κατάντη οι ιχθύες εμφανίζουν μηχανισμούς μάθησης και προσαρμογής όταν συναντούν σημαντικές μεταβολές της ροής, καθώς αρχικά απορρίπτουν ορισμένες περιοχές και εμφανίζουν συμπεριφορά αναζήτησης μέχρι να

προσαρμοστούν στις συνθήκες ροής και να συνεχίσουν την μετανάστευση προς τα κατάντη {24}, ή να επιλέξουν διαφορετική διαδρομή {20}.
Η παρούσα εργασία επιχειρεί να μοντελοποιήσει το μηχανισμό αντίληψης, τις διαφορετικές συμπεριφορές που εμφανίζουν οι ιχθύες και τον τρόπο αντίδρασης με βάση αυτές, αξιοποιώντας μεθόδους από υπάρχοντα μαθηματικά μοντέλα προσομοίωσης συμπεριφοράς ιχθύων κατά την κατάντη μετανάστευση τους. Το μαθηματικό μοντέλο το οποίο παρουσιάζεται απαιτεί την πρότερη επίλυση του υδροδυναμικού πεδίου της περιοχής που εξετάζεται, το οποίο και έγινε με χρήση του υπολογιστικού μοντέλου TELEMAC-2D, το οποίο επιλύει τις εξισώσεις Saint-Venant με πεπερασμένα στοιχεία με χρήση του τυρβώδους μοντέλου k-ε {10}. Στη συνέχεια, προσομοιώνονται οι κινήσεις ιχθύων στην περιοχή μελέτης με σκοπό την βαθμονόμηση και επιβεβαίωση του μοντέλου.

2 ΣΥΝΟΠΤΙΚΗ ΠΕΡΙΓΡΑΦΗ ΤΟΥ ΜΟΝΤΕΛΟΥ

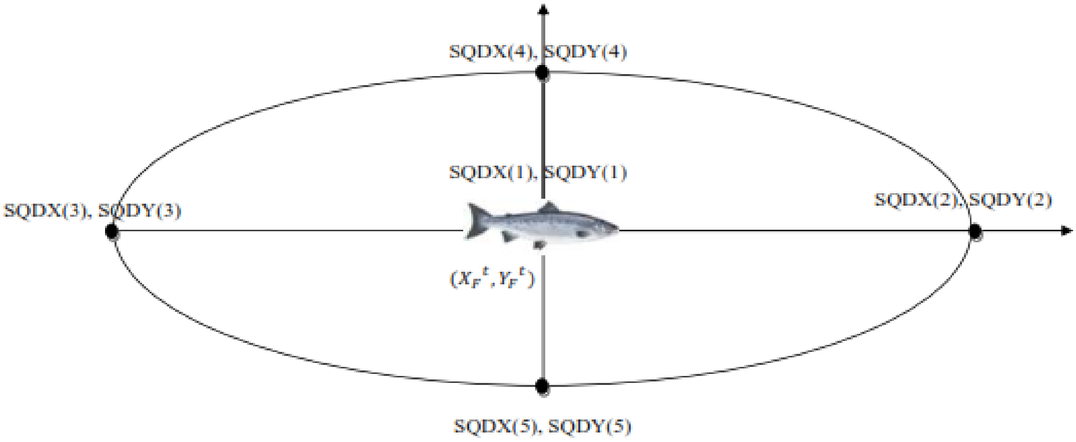
2.1 Βασικές αρχές

Στο παρόν εδάφιο αναφέρονται οι τρεις βασικές αρχές του μοντέλου. Σημειώνεται ότι τα σύμβολα των παραμέτρων που εμφανίζονται στις εξισώσεις αναφέρονται στο κείμενο ή στους Πίνακες 1-5.
1. Κύριο ερέθισμα. Οι ιχθύες, οι οποίοι θεωρούνται 2-D στην παρούσα εργασία, δέχονται ως κύριο ερέθισμα από το πεδίο ροής (υδροδυναμικό ερέθισμα) την τοπική επιτάχυνση ($\mathrm{A_M}^{\mathrm{t}}$), βλ. εξίσωση (1), η οποία προσομοιώνεται με τη λογαριθμική αδιάστατη μορφή της $\mathrm{I_A}^{\mathrm{t}}$, βλ. εξίσωση (2), όπου t είναι η χρονική στιγμή υπολογισμού, και U, V είναι οι ταχύτητες ροής κατά τις διευθύνσεις x και y, αντίστοιχα, ενός Καρτεσιανού συστήματος συντεταγμένων.

$$\mathrm{A_M}^{\mathrm{t}} = \sqrt{(\mathrm{U}\frac{\vartheta \mathrm{U}}{\vartheta \mathrm{x}} + \mathrm{V}\frac{\vartheta \mathrm{U}}{\vartheta \mathrm{y}})^2 + (\mathrm{U}\frac{\vartheta \mathrm{V}}{\vartheta \mathrm{x}} + \mathrm{V}\frac{\vartheta \mathrm{V}}{\vartheta \mathrm{y}})^2} \quad (1)$$

$$\mathrm{I_A}^{\mathrm{t}} = \log_{10}\frac{\mathrm{A_M}^{\mathrm{t}}}{\mathrm{A0}} \quad (2)$$

2. Βασικές συμπεριφορές. Όταν οι ιχθύες αντιλαμβάνονται το υδροδυναμικό ερέθισμα, ακολουθούν μια από τις ακόλουθες συμπεριφορές: (B1) κολυμπούν ακολουθώντας την κατεύθυνση της ροής, (B2) κολυμπούν προς μεγαλύτερες ταχύτητες ροής, αλλάζοντας κατεύθυνση και (B3) κολυμπούν αντίθετα στη ροή. Αρχικά, επιλέγουν μια συμπεριφορά με βάση την τιμή του δείκτη ανίχνευσης (DMETRIC), την οποία στη συνέχεια επιβεβαιώνουν ή όχι με βάση την τιμή του συντελεστή απόφασης (NDECIS).
3. Περιοχή αντίληψης. Η περιοχή εντός της οποίας ένας ιχθύς, αντιλαμβάνεται το υδροδυναμικό ερέθισμα προσδιορίζεται από 5 θέσεις αντίληψης, εκ των οποίων η πρώτη είναι το κέντρο του ιχθύος με συντεταγμένες $\mathrm{X_F}^{\mathrm{t}}$και $\mathrm{Y_F}^{\mathrm{t}}$, δυο στη διεύθυνση x σε αποστάσεις SQDX(2) και SQDX(3), και δυο στη διεύθυνση y σε αποστάσεις SQDY(4) και SQDY(5). Στην περίπτωση 3-D πεδίου ροής υπάρχουν ακόμα 2 θέσεις αντίληψης, πάνω και κάτω από τον ιχθύ.



Εικόνα 1: Σχηματική αναπαράσταση της περιοχής αντίληψης του ιχθύος με τις 5 θέσεις αντίληψης

2.2 Διαδικασία υπολογισμών

Οι υπολογισμοί πραγματοποιούνται με μια σειρά 8 βημάτων που περιγράφονται στη συνέχεια.

Βήμα 1. Καθορισμός και εισαγωγή της περιοχής υπολογισμού. Εισάγονται στο μοντέλο η γεωμετρία της περιοχής εφαρμογής και δομείται το υπολογιστικό πλέγμα. Στην παρούσα εργασία, το πλέγμα είναι 2-D, δομημένο και αποτελείται από 8738 κόμβους.

Βήμα 2. Υπολογισμός και εισαγωγή των χαρακτηριστικών της ροής. Υπολογίζονται σε κάθε κόμβο του πλέγματος οι ταχύτητες ροής με υδροδυναμικό μοντέλο. Στην παρούσα εργασία, χρησιμοποιείται το μοντέλο TELEMAC-2D {4}, το οποίο επιλύει τις εξισώσεις Saint-Venant με πεπερασμένα στοιχεία και τη χρήση του μοντέλου τύρβης k-ε {4} και υπολογίζει το μόνιμο 2-D πεδίο ροής.

Βήμα 3. Υπολογισμός των τοπικών επιταχύνσεων (A_M) σε κάθε κόμβο του πλέγματος από την εξίσωση (1).

Βήμα 4. Καθορισμός του χρονικού βήματος (dt), των συντεταγμένων της αρχικής θέσης του κέντρου του ιχθύος και της κατεύθυνσής του ($\mathrm{FishAngXY}^t$) τη χρονική στιγμή t=0.

Βήμα 5. Υπολογισμός των θέσεων αισθητήρων της περιοχής αντίληψης του ιχθύος. Οι αποστάσεις των θέσεων αισθητήρων υπολογίζονται αρχικά στο τοπικό σύστημα συντεταγμένων με αρχή το κέντρο του ιχθύος και τη διεύθυνσή του. Στη συνέχεια ανάγονται με τη εφαρμογή μητρώου στροφής-μετατόπισης στο Καρτεσιανό σύστημα συντεταγμένων του πεδίου ροής.

Βήμα 6. Υπολογισμός του δείκτη ανίχνευσης και του συντελεστή απόφασης. Με τον υπολογισμό αυτό καθορίζεται η βασική συμπεριφορά του ιχθύος που επιλέγει την κάθε χρονική στιγμή.

Βήμα 7. Υπολογισμός των συνιστωσών $\mathrm{U_F}^\mathrm{t}$ και $\mathrm{V_F}^\mathrm{t}$ της ταχύτητας κίνησης του ιχθύος κατά x και y, αντίστοιχα. Για τον υπολογισμό της ταχύτητας κίνησης του ιχθύος λαμβάνεται υπόψη το μήκος του ιχθύος ($\mathrm{L_F}$).

Βήμα 8. Υπολογισμός της νέας θέσης και κατεύθυνσης του ιχθύος, από τις εξισώσεις (3) και (4), αντίστοιχα. Ο εκθέτης t+dt δείχνει τον υπολογισμό του σχετικού μεγέθους την τελική χρονική στιγμή του κάθε χρονικού διαστήματος των υπολογισμών.

$$\mathrm{X_F}^{\mathrm{t+dt}} = \mathrm{X_F}^\mathrm{t} + (\mathrm{U^t} + \mathrm{U_F}^\mathrm{t}) * \mathrm{dt} \quad \text{και} \quad \mathrm{Y_F}^{\mathrm{t+dt}} = \mathrm{Y_F}^\mathrm{t} + (\mathrm{V^t} + \mathrm{V_F}^\mathrm{t}) * \mathrm{dt} \qquad (3)$$

$$\mathrm{FishAngXY}^{\mathrm{t+dt}} = \mathrm{FishAngXY}^\mathrm{t} + \mathrm{angleXY}^\mathrm{t} \qquad (4)$$

όπου $\mathrm{angleXY}^\mathrm{t}$ είναι η μεταβολή της κατεύθυνσης κίνησης τη χρονική στιγμή t. Η διαδικασία των βημάτων 5-8 επαναλαμβάνεται για το χρονικό διάστημα από t+dt μέχρι t+2dt κ.ο.κ.

2.3 Προσδιορισμός των θέσεων αντίληψης

Οι εξισώσεις και η σειρά υπολογισμών των θέσεων αντίληψης παρουσιάζονται στον Πίνακα 1.

Πίνακας 1: Αποστάσεις προσδιορισμού των θέσεων αντίληψης

$SPDIST^t = \frac{4.5}{I_A{}^t}$ και $RINC^t = 1 + RRSQD * Delta$	
$\mathrm{SQDX^t(1) = 0}$	$\mathrm{SQDY^t(1) = 0}$
$SQDX^t(2) = +SPDIST^t * RINC^t$	$SQDY^t(2) = 0$
$SQDX^t(3) = -SPDIST^t * RINC^t$	$SQDY^t(3) = 0$
$SQDX^t(4) = 0$	$SQDY^t(4) = +SPDIST^t * RINC^t$
$SQDX^t(5) = 0$	$SQDY^t(5) = -SPDIST^t * RINC^t$

2.4 Διαδικασία επιλογής της βασικής συμπεριφοράς

Υπολογίζεται ο δείκτης ανίχνευσης από την εξίσωση (5) με τις εξισώσεις του Πίνακα 2, η τιμή του οποίου καθορίζει την αρχική βασική συμπεριφορά, αλλά και τις τιμές των παραμέτρων γεγονότος $\mathrm{EVENT^t(1)}$, $\mathrm{EVENT^t(2)}$ και $\mathrm{EVENT^t(3)}$, σύμφωνα με τις εξισώσεις του Πίνακα 2. Στη συνέχεια, υπολογίζονται η πιθανότητα προτίμησης της κάθε συμπεριφοράς ιχθύος $\mathrm{P^t}$, η χρησιμότητα της κάθε συμπεριφοράς του $\mathrm{Util^t}$, η μέγιστη χρησιμότητα $\mathrm{UtilMax^t}$, και τελικά ο συντελεστής απόφασης, όπως παρουσιάζεται στον Πίνακα 3. Ο ιχθύς επιλέγει τη συμπεριφορά για την οποία $NDECIS^t \geq 1$.

Πίνακας 2: Σειρά υπολογισμών για τον καθορισμό του δείκτη ανίχνευσης και των παραμέτρων γεγονότος

$\mathrm{DMETRIC^t = \frac{I_A{}^t - I_{mem}{}^t}{I_{mem}{}^t}}$ (5) $\mathrm{I_A{}^t = \log_{10}\frac{A_M{}^t}{A0}}$			
$\mathrm{I_{mem}{}^t(1) = \big(1 - MemAccl(1)\big) * I_A{}^t + MemAccl(1) * I_{mem}{}^{t-dt}(1)}$ $\mathrm{I_{mem}{}^t(2) = \big(1 - MemAccl(2)\big) * I_A{}^t + MemAccl(2) * I_{mem}{}^{t-dt}(2)}$ $\mathrm{I_{mem}{}^t(3) = \big(1 - MemAccl(3)\big) * I_A{}^t + MemAccl(3) * I_{mem}{}^{t-dt}(3)}$ Για t=0: $\mathrm{I_{mem}{}^t(1), I_{mem}{}^t(2), I_{mem}{}^t(3) = I_A{}^t}$			
$DMETRIC^t$	$\mathrm{\geq Thres(1)}$	$\mathrm{\geq Thres(2)}$	$\mathrm{\geq Thres(3)}$
Εφαρμόζεται:	Συμπεριφορά B1	Συμπεριφορά B2	Συμπεριφορά B3
$\mathrm{EVENT^t(1)}$	1	0	0
$\mathrm{EVENT^t(2)}$	0	1	0
$\mathrm{EVENT^t(3)}$	0	0	1

Πίνακας 3: Σειρά υπολογισμών για τον καθορισμό του συντελεστή απόφασης

$\mathrm{P^t(1) = \big(1 - MemBeh(1)\big) * EVENT^t(1) + MemBeh(1) * P^{t-dt}(1)}$ $\mathrm{P^t(2) = \big(1 - MemBeh(2)\big) * EVENT^t(2) + MemBeh(3) * P^{t-dt}(2)}$ $\mathrm{P^t(3) = \big(1 - MemBeh(3)\big) * EVENT^t(3) + MemBeh(3) * P^{t-dt}(3)}$ Για t=0: $\mathrm{P^t(1), P(2)^t, P(3)^t = 0.33}$			
$\mathrm{Util^t(1) = P^t(1) * IntrUtil(1)}$ $\mathrm{Util^t(2) = P^t(2) * IntrUtil(2)}$ $\mathrm{Util^t(3) = P^t(3) * IntrUtil(3)}$ $\mathrm{UtilMax^t = max\,\{Util^t(1), Util^t(2), Util^t(3)\}}$			
$\mathrm{UtilMax^t}$	$\mathrm{Util^t(1) = UtilMax^t}$	$\mathrm{Util^t(2) = UtilMax^t}$	$\mathrm{Util^t(3) = UtilMax^t}$
Εφαρμόζεται:	Συμπεριφορά B1	Συμπεριφορά B2	Συμπεριφορά B3
$NDECIS^t(1)$	$NDECIS^{t-dt}(1) + 1$	0	0
$NDECIS^t(2)$	0	$NDECIS^{t-dt}(2) + 1$	0
$NDECIS^t(3)$	0	0	$NDECIS^{t-dt}(3) + 1$
Για t=0	$NDECIS^t(1) = 1$	$NDECIS^t(2) = 0$	$NDECIS^t(3) = 0$

2.5 Υπολογισμός ταχύτητας ιχθύος για τις τρεις βασικές συμπεριφορές

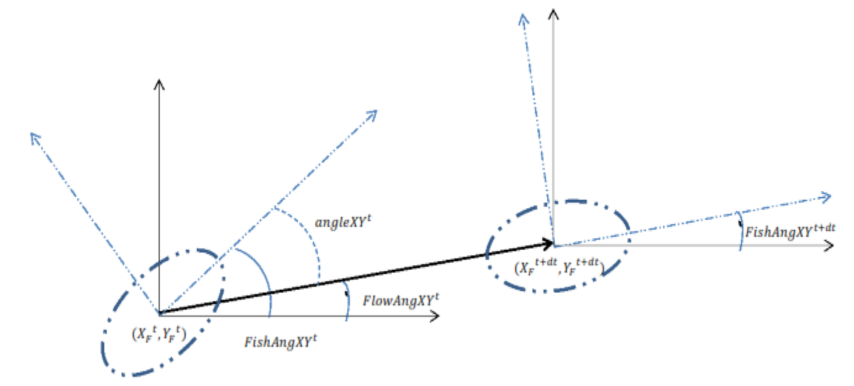
Η μέθοδος και οι εξισώσεις υπολογισμού της ταχύτητας του ιχθύος και της κατεύθυνσής της παρουσιάζονται στον Πίνακα 4. Στην αρχή των υπολογισμών, υπολογίζεται η κατεύθυνση της ταχύτητας ροής $\mathrm{FlowAngXY^t}$, με συνιστώσες $(\mathrm{U^t}, \mathrm{V^t})$ στη θέση του ιχθύος $(\mathrm{X_F}^{t}, \mathrm{Y_F}^{t})$ και η διεύθυνσή του ιχθύος τη χρονική στιγμή t. Για $\mathrm{t = 0, angleXY^t = 0}$ και $\mathrm{FishAngXY^t = 0}$.

$$\mathrm{FlowAngXY^t = tan^{-1}\, V^t/U^t} \qquad (6)$$

Πίνακας 4: Υπολογισμός μέτρου και κατεύθυνσης ταχύτητας κίνησης για τις συμπεριφορές B1, B2 και B3

Συμπεριφορά B1.

$NDECIS^t(1)$	1	2	> 2
$\mathrm{e^{0.005*(NDECIS^t(1)-1)}-1)}$	-	$\geq \mathrm{R}$	$\geq \mathrm{R}$
$\mathrm{angleXY^t}$	$\mathrm{FlowAngXY^t - FishAngXY^t}$	$\mathrm{RRD * 20^o}$	$\mathrm{RRD * 20^o + angleXY^{t-dt}}$
$\mathrm{SpeedFish^t}$	$L_F * (\mathrm{S_{Cruise} + RRSI * (S_{Cruise} - S_{Drift})}$		



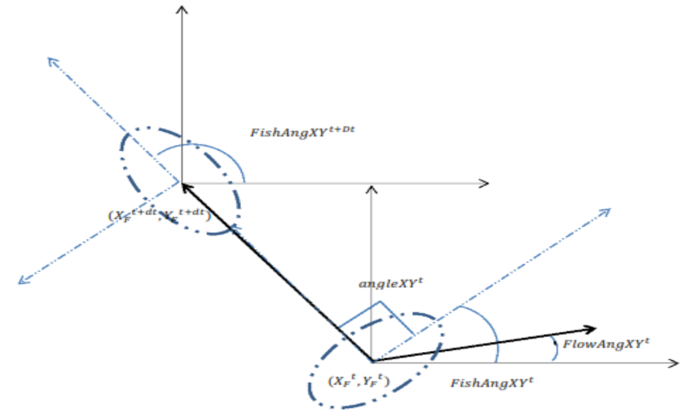
Συμπεριφορά B2.

$\mathrm{NDECIS^t(2)}$	≥ 1
$\mathrm{B2vel^t(2) = 1./\sqrt{U^t(2)^2 + V^t(2)^2}}$ $\mathrm{B2vel^t(4) = 1./\sqrt{U^t(2)^2 + V^t(4)^2}}$	$\mathrm{B2vel^t(3) = 1./\sqrt{U^t(3)^2 + V^t(3)^2}}$ $\mathrm{B2vel^t(5) = 1./\sqrt{U^t(5)^2 + V^t(5)^2}}$

$\mathrm{B2velMin^t = min\,\{B2vel^t(2), B2vel^t(3), B2vel^t(4), B2vel^t(5)\}}$
Οι υπολογισμοί γίνονται για τις θέσεις των αισθητήρων 2,3,4 και 5

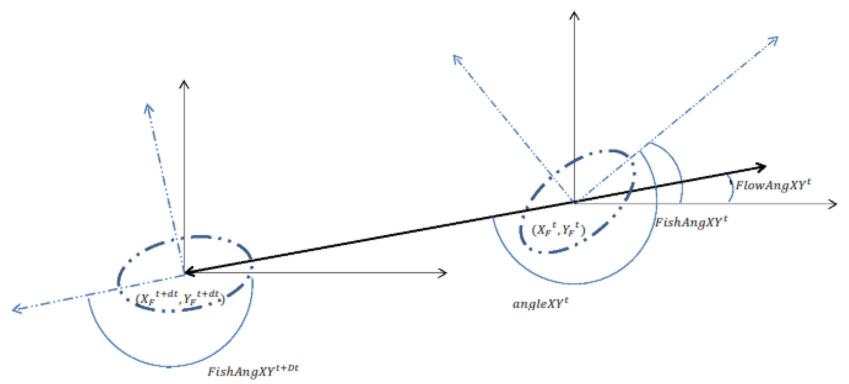
$\mathrm{B2velMin^t}$	$\mathrm{B2vel^t(2)}$	$\mathrm{B2vel^t(3)}$	$\mathrm{B2vel^t(4)}$	$\mathrm{B2vel^t(5)}$
$\mathrm{angleXY^t}$	$\mathrm{RRD * 20^o + 0^o}$	$\mathrm{RRD * 20^o + 180^o}$	$\mathrm{RRD * 20^o + 90^o}$	$\mathrm{RRD * 20^o - 90^o}$

$\mathrm{A_M}^{t} - \mathrm{A_M}^{t-dt}$	< 0	≥ 0
$\mathrm{SpeedFish^t}$	$\mathrm{L_F * (S_{Cruise} + RRSI * (S_{Cruise} - S_{Drift})}$	$\sqrt{\mathrm{U^2 + V^2}} * (1 + 1.5)$



Συμπεριφορά Β3.

$NDECIS^t(3)$	1	> 1
$e^{0.005*(NDECIS^t(3)-1)} - 1)$	-	$\geq R$
$angleXY^t$	$FlowAngXY^t - FishAngXY^t - 180^o$	$\frac{180^o}{I_A{}^t} - FlowAngXY^t$
$SpeedFish^t$	$L_F * S_{Boost}$	$SpeedFish^{t-dt} * (1 - 0.025)$



$$U_F temp^t = SpeedFish^t * \cos(angleXY^t) \quad (7)$$
$$V_F temp^t = SpeedFish^t * \sin(angleXY^t) \quad (8)$$

$$U_F{}^t = U_F temp^t * \cos(FishAngXY^t) - V_F temp^t * \sin(FishAngXY^t) \quad (9)$$
$$V_F{}^t = U_F temp^t * \sin(FishAngXY^t) + V_F temp^t * \cos(FishAngXY^t) \quad (10)$$

Πίνακας 5: Συντελεστές μοντέλου

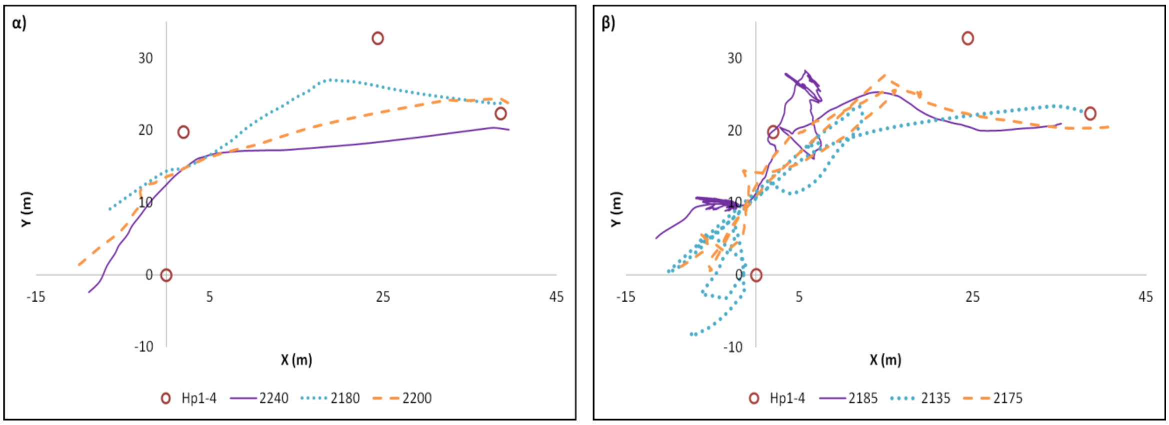
Συμβολισμός	Μεταβλητή	Τιμή	Μονάδες
A0	Ελάχιστη τιμή επιτάχυνσης	10^{-6} {12}	m^2/s
Delta	Ποσοστό τυχαίας αύξησης απόστασης σημείου ελέγχου	2 {13}	-
intrUtil(1)	Εγγενής προτίμηση επιλογής συμπεριφοράς Β1	1 {12}	-
intrUtil(2)	Εγγενής προτίμηση επιλογής συμπεριφοράς Β2	0.3÷1 {12}	-
intrUtil(3)	Εγγενής προτίμηση επιλογής συμπεριφοράς Β3	0.3÷1 {12}	-
MemAccl(1)	Συντελεστής μνήμης προσαρμογής σε συμπεριφορά Β1	0 {12}	-
MemAccl(2)	Συντελεστής μνήμης προσαρμογής σε συμπεριφορά Β2	0÷1 {12}	-
MemAccl(3)	Συντελεστής μνήμης προσαρμογής σε συμπεριφορά Β3	0÷1 {12}	-
MemBeh(1)	Συντελεστής μνήμης συμπεριφοράς Β1	1 {12}	-
MemBeh(2)	Συντελεστής μνήμης συμπεριφοράς Β2	0÷1 {12}	-
MemBeh(3)	Συντελεστής μνήμης συμπεριφοράς Β3	0÷1 {12}	-
R	Τυχαίος αριθμός ομοιόμορφής κατανομής	0÷1 {10}	
RRD	Τυχαίος αριθμός εύρους διεύθυνσης κίνησης	-1÷1	
RRSI	Τυχαίος αριθμός εύρους αύξησης ταχύτητας	-0.5÷0.5	
RRSQD	Τυχαίος αριθμός αύξησης απόστασης σημείου ελέγχου	0÷1 {13}	-
S_{Boost}	Συντελεστής ταχύτητας έκρηξης	6÷10 {15}	s^{-1}
S_{Cruise}	Συντελεστής ταχύτητας πλεύσης	0÷2 {15}	s^{-1}
S_{Drift}	Συντελεστής ταχύτητας συμπαράσυρσης	0.25 {15}	s^{-1}
Thres(1)	Όριο ενεργοποίησης γεγονότος συμπεριφοράς Β1	0 {12}	-
Thres(2)	Όριο ενεργοποίησης γεγονότος συμπεριφοράς Β2	0.84 {12}	-
Thres(3)	Όριο ενεργοποίησης γεγονότος συμπεριφοράς Β3	0.89 {12}	-

3 ΠΕΡΙΠΤΩΣΗ ΕΦΑΡΜΟΓΗΣ

3.1 Περιοχή εφαρμογής.

Μετά από διεξοδική αναζήτηση στη διεθνή βιβλιογραφία, διαπιστώθηκε ότι δεν υπάρχουν διαθέσιμες μετρήσεις πεδίου στην περιοχή ΥΗΕ σε ποταμούς. Για το λόγο αυτό, εφαρμόσαμε το μοντέλο σε τμήμα του ποταμού Konge River στην περιοχή Jedsted Mill Fish Farm στη Δυτική Δανία, 7 km ανάντη της Βαλτικής Θάλασσας, στο οποίο μας διατέθηκαν (βλ. ΕΥΧΑΡΙΣΤΙΕΣ) μετρήσεις πεδίου που αφορούν βάθη ροής, μέσες ταχύτητες ροής και ενδεικτικές πορείες ιχθύων Atlantic Salmon Smolts μήκους L_F=19.1±1.1 cm και βάρους 53.1±9.9g {10}, όπως φαίνεται ενδεικτικά στις Εικόνες 2, 3. Στον Πίνακα 6 δίνονται στοιχεία διέλευσης για τους ιχθύες, όπως προέκυψαν από τα πειραματικά δεδομένα. Με βάση τα βάθη και τις ταχύτητες ροής, υπολογίσαμε στις διατομές των ορίων της περιοχής εφαρμογής Δ1, Δ2 και Δ3 τις παροχές 5.65 m^3/s , 2.95 m^3/s, και 2.60 m^3/s, αντίστοιχα.

Εικόνα 2: Μετρηθείσες ισοϋψείς καμπύλες βαθών ροής και μέσων ταχυτήτων ροής στην περιοχή εφαρμογής. Οι διατομές Δ1, Δ2, Δ3 φαίνονται με άσπρη διαγώνια γραμμή [Πηγή: J. Svendsen, βλ. ΕΥΧΑΡΙΣΤΙΕΣ]



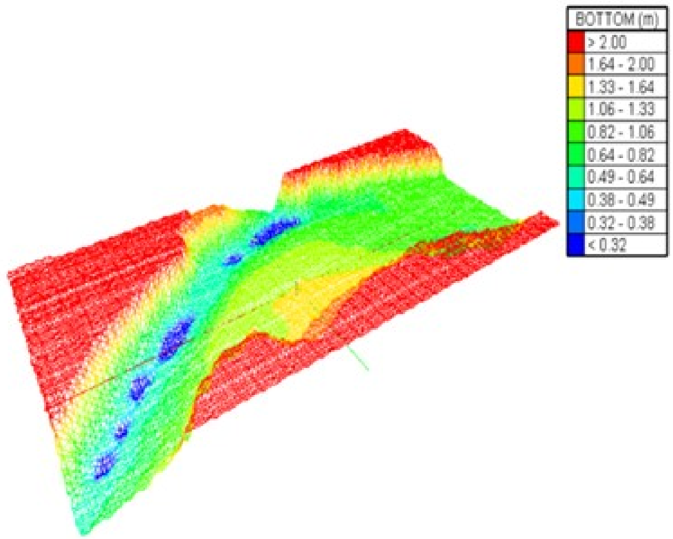
Εικόνα 3: Μετρηθείσες πορείες ιχθύων: (α) χωρίς ξαφνικές αλλαγές κατεύθυνσης, και (β) με ξαφνικές αλλαγές κατεύθυνσης. Οι κυκλικοί δείκτες προσδιορίζουν τις θέσεις τοποθέτησης των δεκτών (hydrophone) που χρησιμοποιήθηκαν στις μετρήσεις

Πίνακας 6: Πειραματικά δεδομένα διέλευσης ιχθύων σε περιοχή μελέτης [Πηγή: {21}]

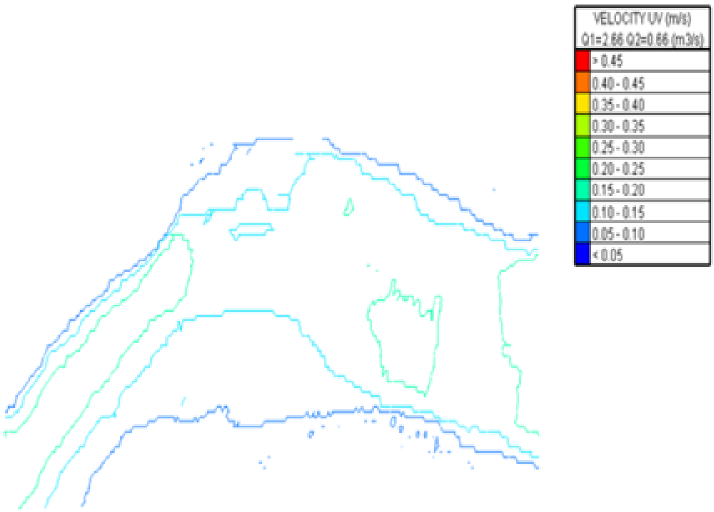
Εξεταζόμενοι παράμετροι	Χωρίς αλλαγές κατεύθυνσης	Με απότομες αλλαγές κατεύθυνσης	Μονάδες
Αριθμός ιχθύων	27	14	-
Χρόνος	162 ± 24	6732 ± 1236	s
Απόσταση	42.3 ± 1.1	353.8 ± 78.2	m
Μέση ταχύτητα	0.48 ± 0.05	0.22 ± 0.05	m/s
Μήκος ιχθύος	19.0 ± 0.2	19.3 ± 0.3	cm

4 ΥΠΟΛΟΓΙΣΜΟΙ ΚΑΙ ΣΧΟΛΙΑΣΜΟΣ

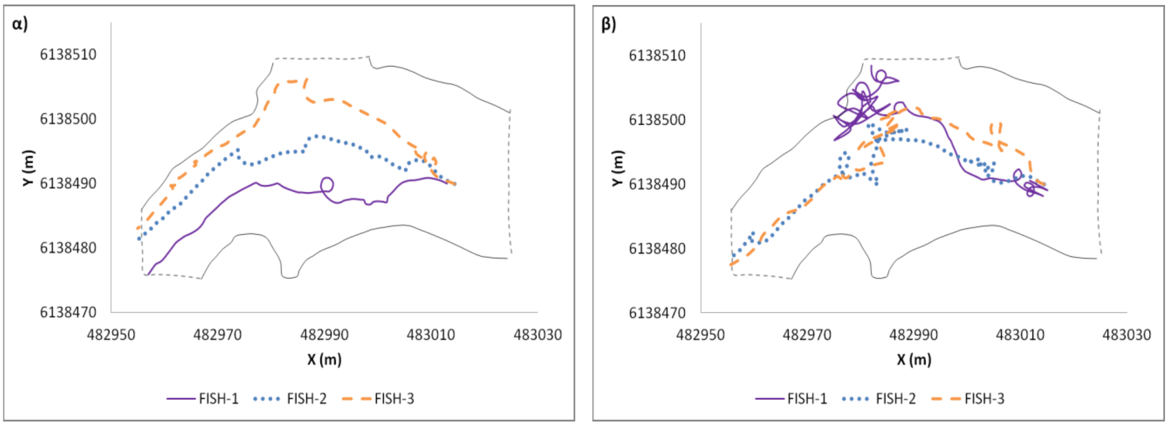
Στα πρώτα δυο βήματα των υπολογισμών (βλ. εδάφιο 2.2) εισαγάγαμε τη γεωμετρία της περιοχής εφαρμογής στο μοντέλο TELEMAC-2D, δομήσαμε το υπολογιστικό πλέγμα του, καθορίσαμε τις οριακές συνθήκες στις διατομές Δ1 (δεδομένη παροχή), Δ2 (δεδομένη παροχή και δεδομένη στάθμη επιφάνειας), και Δ3 (δεδομένη στάθμη επιφάνειας) και πραγματοποιήσαμε τη βαθμονόμηση του με την οποία προσδιορίσαμε τον συντελεστή Manning $(0.065 \div 0.112)$\{7\}, λαμβάνοντας υπόψη τα χαρακτηριστικά της βλάστησης και του υλικού του πυθμένα. Στη συνέχεια, εφαρμόσαμε το βαθμονομημένο TELEMAC-2D για να υπολογίσουμε τα βάθη και τις ταχύτητες ροής του μόνιμου πεδίου ροής σε κάθε κόμβο του υπολογιστικού πλέγματος, όπως φαίνεται στις Εικόνες 4, 5. Με βάση τα υδροδυναμικά χαρακτηριστικά που υπολογίσαμε, εφαρμόσαμε τα υπόλοιπα βήματα υπολογισμών 3-8 για να προσδιορίσουμε τις πορείες των ιχθύων που φαίνονται στην Εικόνα 6. Οι υπολογισθείσες πορείες παρουσιάζουν ποιοτική συμφωνία με τις μετρήσεις που μπορεί να θεωρηθεί ως ικανοποιητική, λαμβάνοντας υπόψη το ότι το μοντέλο βρίσκεται στην αρχική του μορφή και δεν έχει βαθμονομηθεί το μέρος του που αφορά τη συμπεριφορά των ιχθύων. Για την αποτελεσματικότερη βαθμονόμηση του μοντέλου, πραγματοποιήσαμε ανάλυση ευαισθησίας του μοντέλου.



Εικόνα 4: Βάθη ροής



Εικόνα 5: Ταχύτητες ροής



Εικόνα 6: Υπολογισμένες πορείες ιχθύων (α) χωρίς ξαφνικές αλλαγές κατεύθυνσης, και (β) με ορισμένες μόνο ξαφνικές αλλαγές κατεύθυνσης

Πραγματοποιήσαμε την ανάλυση ευαισθησίας για 100 ιχθύες που είχαν την ίδια θέση εκκίνησης, εξετάζοντας αρχικά την επίδραση 13 συντελεστών του μοντέλου, με αρχικό στόχο την αναγνώριση των σημαντικότερων από αυτούς και τελικό σκοπό την αποτελεσματική βαθμονόμηση του μοντέλου. Για κάθε σειρά υπολογισμών, προσδιορίσαμε τον μέσο χρόνο διέλευσης των ιχθύων από την περιοχή εφαρμογής, το συνολικό μήκος της πορείας που ακολούθησαν, τη μέση ταχύτητα για τα οποία υπήρχαν και τα πειραματικά δεδομένα του Πίνακα 6, καθώς και τον αριθμό των ιχθύων, για τους οποίους ενεργοποιήθηκαν οι συμπεριφορές B1, B2, και B3. Συνοψίζουμε στον Πίνακα 7 τους υπολογισμούς για τους συντελεστές με τη σημαντικότερη μεταβολή, που ήταν οι Thres(2), Thres(3) και S_{Cruise}. Για τις αρχικές τιμές των συντελεστών, υπολογίσαμε για την πορεία ιχθύων χωρίς ξαφνικές αλλαγές κατεύθυνσης, το χρόνο διέλευσης ίσο με 157.7 s και τη μέση ταχύτητα των ιχθύων ίση 0.47 m/s, τιμές που είναι πολύ κοντά στις μετρημένες (162.0 s και 0.48 m/s, αντίστοιχα, βλ. Πίνακα 6). Όμως, η τιμή της απόστασης που υπολογίσαμε ίση με 74.5 m ήταν πολύ μεγαλύτερη της πειραματικής τιμής, γεγονός που δείχνει ότι απαιτείται βελτίωση της διαδικασίας βαθμονόμησης. Στη συνέχεια, μεταβάλλαμε τις τιμές των συντελεστών Thres(2) και Thres(3), προσδιορίσαμε τις τιμές τους, για τις οποίες ενεργοποιούνται οι συμπεριφορές B2 και B3 και διαπιστώσαμε ότι αυτό συμβαίνει όταν Thres(2)<0.21 και Thres(3)<0.135. Τέλος, θέσαμε τις τιμές Thres(2)=0.08 και Thres(3)=0.09 και διερευνήσαμε εκ νέου την επίδραση των υπολοίπων 11 συντελεστών του μοντέλου. Όπως συνοψίζεται στον Πίνακα 8, παρατηρήσαμε ότι επιδρούν σημαντικά οι συντελεστές MemBeh(2), MemBeh(3), S_{Boost} και S_{Cruise}.

Πίνακας 7: Επίδραση συντελεστών του μοντέλου

Συντελεστές			**Χρόνος** (s)	**Απόσταση** (m)	**Μέση ταχύτητα** (m/s)	**B1**	**B2**	**B3**
Αρχικές τιμές (βλ. Πίνακα 5)			157.7	74.5	0.47	100	0	0
Thres(2)	-50%	0.42	157.7	74.5	0.47	100	0	0
	-75%	0.21	160.2	74.8	0.47	100	50	0
	-85%	0.13	191.7	87.5	0.46	100	95	0
	-90%	0.08	220.1	98.1	0.45	100	100	0
Thres(3)	-50%	0.45	157.7	74.5	0.47	100	0	0
	-75%	0.22	157.7	74.5	0.47	100	0	0
	-85%	0.135	153.9	75.5	0.48	100	0	11
	-90%	0.09	171.5	92.5	0.53	100	0	49
S_{Cruise}	min	0	451.9	67.9	0.15	100	0	0
	max	2	157.7	74.5	0.47	100	0	0

Πίνακας 8: Επίδραση των συντελεστών του μοντέλου για Thres(2)=0.08 και Thres(3)=0.09

Συντελεστές			**B1**	**B2**	**B3**	**B1/fish**	**B2/fish**	**B3/fish**
Αρχικές τιμές			100	99	46	92	31	8
MemBeh(2)	min	0	100	99	46	92	31	8
	max	0.999	100	0	49	74	0	12
MemBeh(3)	min	0	100	63	100	197	28	35
	max	0.998	100	99	46	92	31	8
S_{Boost}	min	6	100	100	49	94	23	20
	max	10	100	99	46	92	31	8
S_{Cruise}	min	0	100	100	51	249	49	2
	max	2	100	99	46	92	31	8

5 ΣΥΜΠΕΡΑΣΜΑΤΑ – ΠΡΟΤΕΙΝΟΜΕΝΗ ΕΡΕΥΝΑ

5.1 Συμπεράσματα εργασίας.

Από την παρούσα εργασία προέκυψαν τα ακόλουθα συμπεράσματα:

1. Είναι δυνατή η προσομοίωση της κίνησης ιχθύος με το προτεινόμενο Μοντέλο Συμπεριφοράς Ιχθύος.

2. Οι ιχθύες μπορούν να αντιληφθούν αλλαγές στην επιτάχυνση της ροής και να επιλέξουν συμπεριφορά κίνησης με βάση αυτές, ενεργοποιώντας έτσι τις συμπεριφορές B2 και B3 που προσομοιώθηκαν στο ΜΣΙ. Η ενεργοποίηση των συμπεριφορών που προσομοιώνουν την συμπεριφορά των ιχθύων είναι εφικτή μέσω της βαθμονόμησης του προτεινόμενου μοντέλου.

3. Οι σημαντικότεροι συντελεστές του ΜΣΙ είναι οι συντελεστές ορίου για το δείκτη ανίχνευσης THRES(2) και THRES(3). Με κατάλληλη επιλογή των παραπάνω ορίων γίνεται η ενεργοποίηση της συμπεριφοράς B2 και B3, , και έπειτα αρχίζουν να επιδρούν και οι λοιποί συντελεστές του ΜΣΙ στη λήψη απόφασης κίνησης.

4. Το μοντέλου αδυνατεί να προσομοιώσει το σύνολο των συμπεριφορών και της πολυπλοκότητας κίνησης των ιχθύων και πιθανών απαιτείται προσομοίωση επιπλέον συμπεριφορών.

5.2 Προτεινόμενη έρευνα.

Η εφαρμογή του προτεινόμενου μοντέλου είναι ικανή να προσομοιώσει ορισμένες βασικές συμπεριφορές κίνησης ιχθύων. Απαιτείται ωστόσο περαιτέρω έρευνα με σκοπό την αποτελεσματική του χρήση και την προσομοίωση του συνόλου των κινήσεων των ιχθύων. Προτείνονται επομένως ως αντικείμενα μελλοντικής έρευνας:

1. Περαιτέρω ανάλυση των δεδομένων κίνησης των ιχθύων, συνδυάζοντας την θέση τους στο υδροδυναμικό πεδίο, την ταχύτητα και την κατεύθυνση κίνησής τους, με στόχο την καλύτερη κατανόηση των παραγόντων που επηρεάζουν τις αποφάσεις κίνησης. Μελέτη επίδρασης και άλλων περιβαλλοντικών ερεθισμάτων (πχ θερμοκρασία και ποιότητα υδάτων) στη λήψη αποφάσεων.

2. Βελτίωση των διεργασιών του μοντέλου, με σκοπό την αποτελεσματικότερη προσομοίωση των συμπεριφορών που ήδη περιγράφονται από αυτό. Σε επόμενο στάδιο προτείνεται και η προσομοίωση επιπλέον συμπεριφορών που εμφανίζονται στην βιβλιογραφία και προσομοίωση της κίνησης στον τρισδιάστατο χώρο.

3. Εφαρμογή του προτεινόμενου μοντέλου και σε άλλες περιοχές μελέτης, για τις οποίες υπάρχουν πειραματικά δεδομένα, καθώς και για άλλες περιπτώσεις ιχθύων, με στόχο τη διεύρυνσή του αλλά και την ανάπτυξη της προσαρμοστικότητάς του σε διαφορετικά πεδία ροής και γεωμετρίες περιοχής.

1 INTRODUCTION

1.1 General

The need for water supply, storage and production of energy has been addressed by human activity in the form of hydraulic structures, such as large or smaller dams or other structures that fragment river systems. The fore mentioned structures form an artificial barrier in the river flow that affects the surrounding ecosystem and threatens fish population in rivers. Hence, from the early 20th century attempts have been made to address the problem, by studying fish behavior and interaction with artificial structures and the development of structures that facilitate unobstructed fish passage during upstream and downstream migration.

1.2 Background on fish behavior models, Research questions and hypotheses

There have been considerable efforts on the development of fish passes since the beginning of the 20th century. The main focus of the scientific research and experiments were focused on the design of fish passes, suitable for salmonids species. Especially for upstream fish migration attempts on fishway structures have been found since the end of the 19th century in North America. Over the decades there has been significant development on the design and effectiveness of such structures, especially regarding upstream fish migration, but failing to reach effectiveness, capable of preserving and protecting endangered fish population.

New legislation procedures (EU, Water Framework Directive (WFD), 2000; EC Council Regulation No1100/2007; Canadian Species at Risk Act, 2002) have addressed the need for aquatic ecosystems to retain a "good" ecological status, as well as secure the protection of endangered species. Greece in response to those regulations, has implemented similar legislation to address the issue, such as the Hellenic Eel Management Plan (Koutsikopoulos, C., 2009). Key factor for the fore mentioned directives and legislation is the unobstructed passage of fish during upstream and downstream migration, through fish passes.

The need for maximum efficiency for fishway structures has transferred the focus of scientists and engineers tackling the problem, from empirically testing and applying fish pass designs to understanding the procedure of decision making and behavior of fish. By analyzing and modeling fish behavior, engineers would be able to design cost efficient fish passage with high fish passage percentage.

The main focus of the present work lies in understanding and modeling fish behavior and is based on the following key **Research Questions**:

i. **Via what means is it possible to analyze and determine fish behavior and movement in an aquatic environment, both upstream and downstream of a hydraulic structure?**

ii. **How can we express that behavior in a mathematical form, i.e. a mathematical model?**

Research value of presented work: By addressing the above research questions, it will be made possible for fish passes to be designed and positioned in a way that actively guides the fish to select a safe medium while migrating. As a result fish will be able to find the entrance of a fish passage structure and negotiate it without delay, while avoiding routes associated with high mortality rates, i.e. passage via turbine.

In order to address the above main research questions, several sub-questions have to be considered such as:

i. What attributes are related with fish behavior and movement?
ii. Through what techniques and methods is it possible to model fish behavior?
iii. Is a fish behavior model dependent on fish species and area characteristics?
iv. How can we validate a model for simulating fish movement?

Simulating fish behavior appears to be quite demanding, and the researcher needs to apply knowledge from various sciences, i.e. Computational Fluid Dynamics, Biology and Ichthyology. Knowledge gained from experiments must be also applied for an accurate computational simulation.

Incorporating theoretical and experimental knowledge concerning fish behavior into a mathematical model can be as we have seen a quite vexing procedure. Therefore, a series of **Research Hypotheses** have to be made, to allow the researcher to tackle this problem. For the present model the main **Research Hypotheses** were:

i. Simulated fish movement is dependent on decision, which can be summarized in a set of behavior responses (see Chapter 2 Theoretical and Mathematical Background).
ii. Each species reacts to a specific set of stimuli which activate certain behavior responses, regardless of area characteristics.
iii. Perception area for attributes that activate behavior responses is determined through a "Sensory Ovoid" in the surrounding fluid.
iv. For the calibration of the proposed model, either experimental or field data is needed.

1.3 Contents

In the present work, a background literature review, on the theoretical and mathematical knowledge regarding fish behavior was conducted to determine attributes that influence fish behavior and existing methods of simulating that behavior. Utilizing existing knowledge on behavior models, a fish behavior model is developed and its governing equations are described. The resulting computational code is also presented along with its main parts. Finally the proposed behavior model is calibrated and verified using a case study with field data on fish dynamic positioning in a river. The present work constitutes a part of the Program for the promotion of the exchange and scientific cooperation between Greece and Germany, IKYDA, entitled "Development of an integrated mathematical model for the design of fish-passes in small hydroelectric power plants".

1.4 Contents

Including the introduction, the present work consists of 5 main chapters:

- **Chapter 2** presents the conducted literature review, as well as the mathematical and theoretical background needed for the present work.

- **Chapter 3** describes every aspect of the proposed model and the way that the model executes fish movement calculations.

- **Chapter 4** presents the case study, which was selected for applying the proposed fish behavior model, and describes the process of analyzing obtained data for the selected area.

- **Chapter 5** describes the process of setting up and calibrating the hydrodynamic model in order to calculate the hydrodynamic characteristics of the case study area.
- **Chapter 6** describes the application of the proposed model for the case study and presents a sensitivity analysis for validating the fish behavior model.
- **Chapter 7** summarizes and discusses the results of this study, while proposing suggestions for future research.

2 THEORETICAL AND MATHEMATICAL BACKGROUND

2.1 General

To simulate fish behavior, we need to use knowledge from many sciences, such as Ichthyology, Computational Fluid Mechanics and Computer Science. In this chapter, we present the basic theoretical background needed to understand fish behavior, and to be able to model this behavior. Indicative computational models, simulating fish behavior are also presented.

2.2 Types of fish migration

Fish migration is an extremely complex procedure that has to take into account different fish attributes, in respect to their species. According to Tuys (2012) the phenomenon of migration is now examined under the purview of behavioral ecology, as fish find their way in many aspects just like humans do˙ with orientation, piloting and navigation. This complex behavior has to be taken into account for the efficient modeling of fish movement.

There are two main terms for the classification of fish migrations in respect with their migration patterns during their life cycle: **Anadromous** and **Catadromous** fish.

Anadromous migratory species grow in the sea until they reach sexual maturity and then migrate into fresh water, where they travel upstream to find a suitable spawning area in a river. After they hatch young anadromous fish stay in the stream for about a year, until they become smolts and begin to move downstream to reach the ocean. A typical example of anadromous fish is the Atlantic salmon and the brown trout.

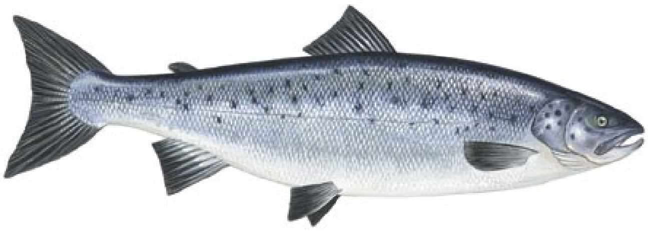


Figure 2.2-1: Atlantic salmon (*Salmo salar*) [source: (*European commission, https://ec.europa.eu/fisheries/marine_species/farmed_fish_and_shellfish/salmon_el*)]

Figure 2.2-2: Brown trout (*Salmo trutta*) [source: (*U.S. Fish & Wildlife Service, https://www.fws.gov/mountain-prairie/fish/fish.html*)]

Typical migration characteristics of the Atlantic salmon (Salmo salar) (Thorstad et al., 2011), are presented in Table 2.2-1.

Table 2.2-1: Typical migration characteristics of Atlantic salmon (*Salmo salar*)

Migration Type	**Time Period**	**Age** (years)	**Weight** (g)	**Length** (cm)	**Water Temperature** (C°)
Downstream	Spring & early Summer	1-8	10-80	10-20	≥8
Upstream	May - October	1-5	500 - 25000	45-135	

Catadromous species on the other hand follow the opposite migratory pattern, as they grow and feed in fresh water and when they mature they travel downstream to the ocean to reach their spawning grounds. The best-known catadromous species are the European eels.

Figure 2.2-3: European eel (*Anguilla anguilla*) [source: (*European commission, https://ec.europa.eu/fisheries/marine_species/wild_species/eel_en*)]

In the present work, the simulation of downstream migration anadromous fish species was attempted, salmon in particular. The following theoretical and mathematical background given in the present work is focused on fish physiology similar to that of the Atlantic Salmon.

2.3 Detection mechanism and detection range

2.3.1 Sensory signals

Fish are able to navigate utilizing multiple sensory organs, which provide them with information about their environment. The most important sensory cues perceived by fish relate to:

1. vision,
2. hearing,
3. chemosensory perception,
4. mechanoreception,
5. electroreception and
6. magnetic orientation (Tuys, 2012).

2.3.2 Lateral line system

Modeling fish behavior in modern literature focuses mainly on sensory signals related to mechanoreception, which is perceived through the lateral line system and plays a critical part in fish navigation in water bodies.

The **lateral line**, as shown in Figure 2.3-1 is a system of sense organs that can be found in fish, enabling them to detect movement and vibrations in the surrounding water with the use of epithelial cells (hair cells). The hair cell organs respond to hydrodynamic disturbances in the surrounding flow field and provide information about the animal's 3-D position and its relationship to other entities in the environment. The lateral line system is thought to form hydrodynamic images of the surrounding moving and stationary objects, similar to the visual images created by the visual system (Coombs and van Netten, 2006).

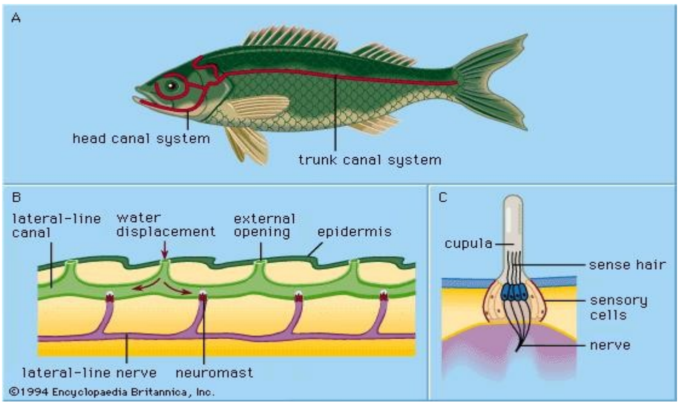


Figure 2.3-1: Lateral line system of fish [source: (*Encyclopaedia Britannica, Inc., 1994*)]

2.3.3 Detection volume

Fish detect signals and acquire information from their environment (such as distortions generated by stationary bodies in ambient currents, e.g. a rock in a stream) within a volume that surrounds fish. This volume can be modeled as symmetrical (sphere) or distorted (ellipsoid) (Goodwin et al., 2001); its dimensions depend on the lateral system or simply on fish length and are usually assumed to be equal to a number of fish body lengths (Coombs, 1999).

Goodwin et al. (2001) in their ELAM model named this volume "sensory ovoid" and its dimensions Sensory Query Distances (SQD), as shown in Figure 2.3-2. Sensory Query Distances are related to model time step $\Delta t = 2s$, fish body length $S_f = 0.2m$, and operating range of sensory system in a $1.0s$ increment equal to $D_a = 2$ (body lengths). Thus, SQDs are calculated as:

$$SQD = \Delta t * S_f * D_a \tag{2.3-1}$$

The SQD values may be modified to reflect differences in fish perception, regarding for example fish physiological condition, time of the day and water quality (Goodwin et al., 2006). SQD values should be determined at the preprocessing stage of simulating fish movement but can also vary during simulation in respect to the fore mentioned conditions.

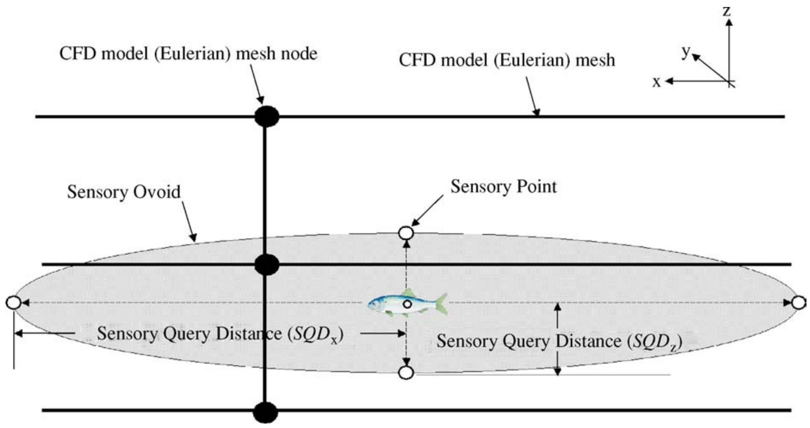


Figure 2.3-2: Two-dimensional view of a fish sensory ovoid [source: (Goodwin et al., 2006)]

2.4 Movement, behavior responses and learning

2.4.1 Non-random movement

Fish were initially considered by the scientific community to drift passively with the flow during downstream migration or move randomly forward. It was later determined that fish actively orient themselves and swim based on behavior choices, while also incorporating some random movement. Fish behavior and consequently fish movement is based on responses to a certain environmental stimulus. The response depends on the intensity of the respected stimulus and elicits a directed nonrandom movement, which is called "taxis" (Tuys, 2012).

The most common and important of these "taxis" are:

1. **Phototaxis**, is related to light. Orientation and movement is affected by light. There have also been reports indicating differences in behavior when fish are provided with a light stimulus, exhibiting elevated responsiveness (avoidance) behavior (Vowles and Kemp, 2012). Fish have also been monitored to adopt a non avoidance behavior (88%) during the day than when dark (55%) indicating a relation between light and behavior responses associated with movement (Vowles et al., 2014).

2. **Thermotaxis**, is cued by water temperature. Nocturnal migration for example is known to occur at temperatures of around $12C^o$ (Thorstad et al., 2011). Other studies have also shown correlation between upstream migration and water temperature (Svendsen and Koed, 2004).

3. **Geotaxis,** which is related to gravity. Fish respond to gravity through their inner ear and react to maintain or change swimming depth.

4. **Thigmotaxis,** which is related to touch. Fish are sensitive to changes in water pressure and acceleration and utilize such stimuli to detect structures when in close proximity and orient themselves to it or to detect and avoid obstacles. Thigmotaxis is a key component in fish, as an avoidance behavior and there have been a number of models incorporating behavior responses based on the proximity to a structure (Haefner and Bowen, 2002; Lemmasson et al., 2008).

5. **Rheotaxis,** which is the way fish position themselves in respect to the flow direction. A positive rheotaxis refers to fish that are oriented up-stream facing the flow, in contrast to negative rheotaxis, where fish are oriented down-stream and swim with the direction of the flow. Behavior models simulate downstream fish migration

assuming negative rheotaxis as a basic behavior, $a = 0^o$, and fish orientation is calculated in respect to flow direction $a \in [-180^o, 180^o]$ (Goodwin et al. 2014; Arenas et al., 2015).

6. **Biotaxis,** which is related to other organisms, who act as a stimulus. Predator prey interactions or movement related to fish schooling are typical examples of biotaxis.

The present work attempted to simulate *Thigmotaxis* and *Rheotaxis* as nonrandom movement behaviors.

2.4.2 Swimming speed classes

Webb (1998) identified the following 3 classes of fish swimming speed that are interconnected with fish behavior:

1. Sustained swimming,
2. prolonged swimming, and
3. burst or sprint swimming

In sustained swimming, fish assume a low speed for navigating through the stream without fatigue. Sustained swimming in downstream migration enables fish to swim in the downstream direction, facing downstream (negative rheotaxis) or upstream (positive rheotaxis).

Prolonged swimming is mainly used as a reaction mechanism to avoid possible obstacles, during which fish experience fatigue (Katopodis, 2005).

Fish assume burst swimming to avoid immediate danger, either by collision to an obstacle or after detection of a predator; thus, burst swimming is related to thigmotaxis or biotaxis.

Indicatively, the characteristics of speed classes for Atlantic salmon are shown in Table 2.4-1.

Table 2.4-1: Characteristics of different swimming speed classes for Atlantic salmon (*Salmo salar*)

Classes of speed	Speed (Lenghts/s)	Duration (s)
Sustained	0-2	indefinitely
Prolonged	2-6	20-1800
Burst or sprint	6-10	<20

2.4.3 Fish Behavior Responses and their activation

The present work attempts to model fish behavior responses, related to differences in hydrodynamic stimuli. Such responses can be described, with the fore mentioned taxis: Thigmotaxis, Rheotaxis and Geotaxis in particular. In modern literature a series of behavior responses have been determined, the most important of which are presented below.

Haefner and Bowen (2002) examined fish behavior through a louver-type fish collection facility (Tracy Fish Collection Facility) that is located in the Central Valley of California (USA), as shown in Figure 2.4-1, and developed a mathematical model that solves the equations of motion for fish movement according to:

1. Physical forces implied by the flow field, and
2. simple modes of behavior to avoid the obstacle, which are the wall or the louver panel that are virtually the "danger".

Haefner and Bowen (2002) determined 4 **behavior responses** that are activated_based on the distance of the fish to the "danger" as follows:

1. No danger is detected. Then, sustained swimming is used.
2. Danger is detected within distance of 1.0 fish length. Then, prolonged swimming is applied.
3. Danger is detected within distance of 0.5 fish length. Then, burst swimming is applied.
4. No danger after burst swimming. Then, reverse swimming is used.

When fish detect the "danger" and activate prolonged or burst swimming; firstly, they turn with the minimum angle that is required to avoid "danger".

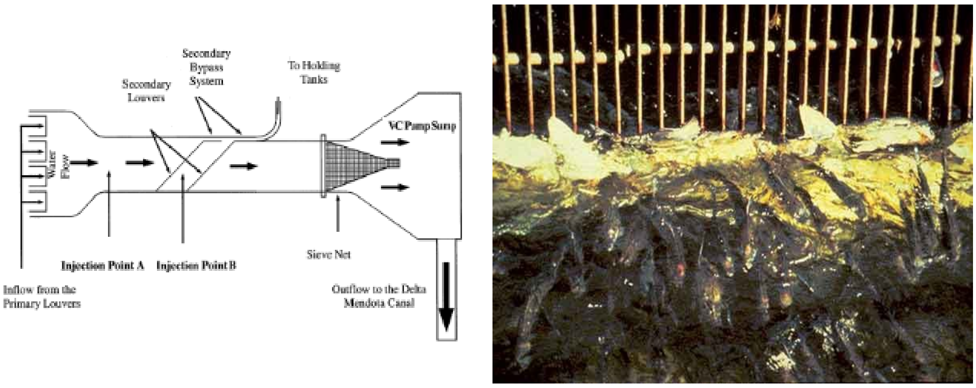


Figure 2.4-1: (a) Schematic of the secondary louver channel at Tracy Fish Collection Facility [source: Haefner and Bowen et al. (2002)], and (b) louver panel used as behavioral barrier [source: Food and Agriculture Organization of the United Nations, http://www.fao.org/docrep/004/Y2785E/y2785e03a.html]

Goodwin et al. (2006) examined the downstream fish passage systems in 3 hydropower dams on Columbia and Snake rivers of the Pacific Northwest, USA. They developed a mathematical model and applied it to simulate 3D movement patterns of individual downstream migrating salmon.

Goodwin et al. (2006) determined 4 behaviors that are activated_based on (1) hydraulic strain, (2) water velocity, and (3) pressure gradient, which are the following:

1. B1: Swim with the flow vector.
2. B2: Swim towards increasing water velocity to minimize hydraulic strain.
3. B3: Swim towards decreasing water velocity or against the flow vector to minimize strain.
4. B4: Swim towards acclimatized pressure (depth).

Lemasson et al. (2008) extended the work of Haefner and Bowen (2002) and using data derived from experiments in a small-scale physical model of the Tracy Fish Collection Facility, they introduced mainly stochasticity in the model of Haefner and Bowen (2002) and proposed the following 5 behavior rules.

1. When fish maneuver to avoid "danger", their intended orientation is drawn from a uniform distribution (randomized) bounded by angles leading away from either the wall, or the louver.

2. Fish detect "danger" within distance of 1.5 fish length and use prolonged swimming.
3. Fish do not consider channel walls as danger, but they see them as "neutral"; thus, channel walls elicit alignment behavior. The louver panel continues to be "danger" for the fish; thus, it elicits repulsive behavior.
4. During their movement, fish were undergone through unpredictable shifts in intended speed and orientation (in regular time intervals of 0.3 secs), which were drawn from appropriate distributions found by experimental data (gamma distribution for speed and wrapped normal distribution for orientation).
5. Fish are attracted towards the wall on the bypass side of the channel in their movement.

Indicative virtual fish paths are shown in Figure 2.4-2.

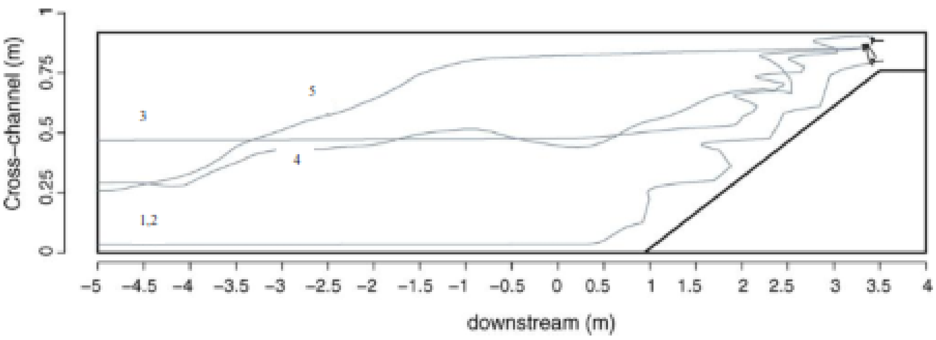


Figure 2.4-2: Virtual fish paths depending on behavior rules 1-5. The straight diagonal line is the louver panel and the bypass is at the top right [source: (Lemasson et al., 2008)]

Vowles et al. (2014) examined the behavior of downstream migrating salmon in an experimental flume, upstream of a rectangular orifice weir, which is shown in Figure 2.4-3. They highlighted the potential of using "signals", such as flow accelerations and light conditions, to repel fish from dangerous areas, such as turbine intakes, and determined the following 5 initial behavioral response types:

1. Swim actively with the bulk flow in the downstream direction.
2. Drift (fish velocity=0) passively with the bulk flow in the downstream direction.
3. React, switch orientation (facing upstream) and continue moving in the downstream direction.
4. Reject, stop moving downstream and hold within regions of high velocity gradients, as shown in Figure 2.4-2(a).
5. Retreat and escape upstream swimming against the flow with speed higher relative to water, as shown in Figure 2.4-2(b).

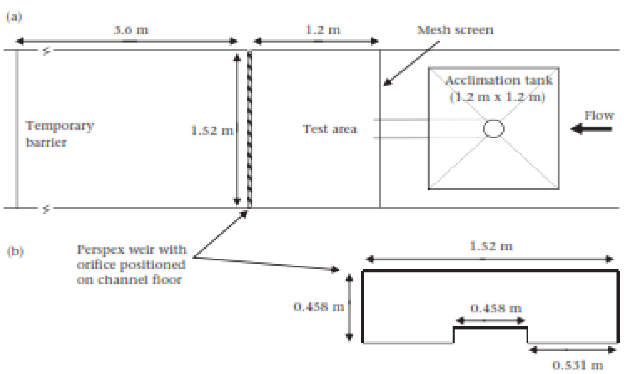


Figure 2.4-3: (a) Plan view of the experimental channel, and (b) side view of orifice weir [source: (Vowles et al., 2014)]

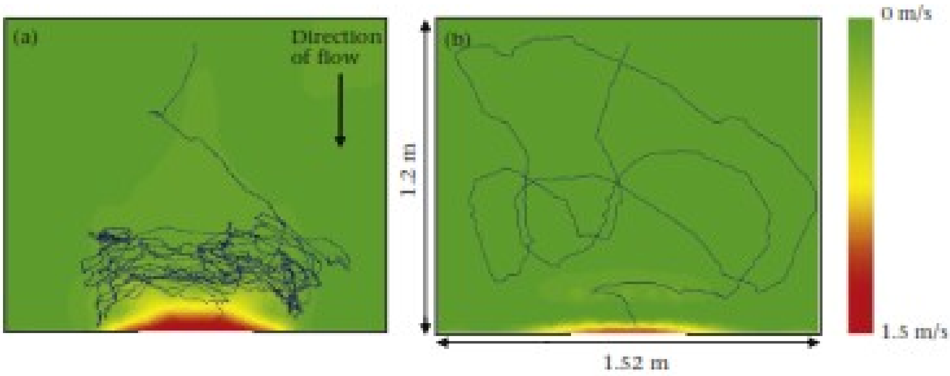


Figure 2.4-4: Velocity profile upstream of orifice weir.
(a) High velocity gradient; the response is "Reject", and
(b) low velocity gradient; the response is "Retreat" [source: (Vowles et al., 2014)]

2.4.4 Learning behavior

During migration fish tend to experience multiple changes in the environmental stimuli they perceive as they travel upstream or downstream. Therefore, adaptation and habituation to hydrodynamic conditions plays an important role in navigating through a stream. This process of adaptation to persistent hydrodynamic stimuli can be also expressed through their lateral line system, where a hair cell's response to a sustained stimulus declines with time (Coombs and van Netten, 2006). This learning behavior allows them to evaluate possible threats and avoid certain hydrodynamic conditions until they are habituated to them.

Milling or oscillatory behavior is thought to be connected to the process of habituation and acclimatization to an area and its hydrodynamic characteristics. Milling behavior has been documented in areas where fish are exposed to a high velocity gradient. In that case fish originally rejected certain locations with greater water accelerations and showed milling behavior, until they eventually passed through that area (Vowles et al., 2014). Such behavior responses could be explained by assuming that fish became acclimatized after some time, to the specific stimuli they initially rejected. Other studies also showed milling behavior near a water withdrawal zone which resulted in a number of fish entering an originally rejected path (Svendsen et al., 2011).

This acclimatization effect can be integrated in a computational model, by utilizing an adaptation coefficient to the perceived stimuli as a relaxation factor to previously identified values of the same stimuli (m_{strain} for strain, m_d for depth acclimatization e.t.c) (Goodwin et al., 2006). For example, if we consider the intensity of total strain, $I(t)$, perceived by fish as a stimulus then the acclimatized value of total strain, $I_a(t)$, perceived by fish can be modeled with a relaxation factor of m_{strain} , with a value between 0 and 1, as:

$$I_a(t) = (1 - m_{strain}) * I(t) - m_{strain} * I_a(t-1) \quad (2.4\text{-}1)$$

As a result, the acclimatized strain is a tradeoff of the total strain perceived at the current time interval and the already acclimatized strain that is stored in its memory.

2.5 Existing Mathematical and computational models

There exist various mathematical models for fish behavior in the literature. A background research and review of the existing models has determined the following ones as the most sophisticated, highlighting their main attributes and functions (Giannoulis, 2015). The present model was based on the main concepts already presented by the models below, and the one presented by Goodwin et al. (2014) in particular.

2.5.1 Haefner and Bowen, 2002; Lemasson et al., 2008

The main aspects of the model of Haefner and Bowen (2002) are:

1. The model perceives the fish as a single 2D body,
2. fish navigate through the flow field according to Newtonian forces present in the medium and water velocities provide the physical forces acting on a fish,
3. fish use the basic survival instinct of obstacle avoidance,
4. the behavior and physiology of the fish determine its reaction to obstacles, and
5. fish position is updated by the equations of motion through solving five ordinary differential equations using a fourth order Runge-Kutta method.

The equations of motion solved by the model are:

$$\frac{du_{f,x}}{dt} = 0.5 * \rho * S_a * (U_x)^2 * \frac{(C_f + C_p)}{m_v} + \frac{P_x}{m_v} \quad (2.5\text{-}1)$$

$$\frac{du_{f,y}}{dt} = 0.5 * \rho * S_a * (U_y)^2 * \frac{(C_f + C_p)}{m_v} + \frac{P_y}{m_v} \quad (2.5\text{-}2)$$

$$\frac{dx_f}{dt} = u_{f,x} \quad (2.5\text{-}3)$$

$$\frac{dy_f}{dt} = u_{f,y} \quad (2.5\text{-}4)$$

$$\frac{dO}{dt} = -f(M) \quad (2.5\text{-}5)$$

where, $U = u_w - u_f$ is the relative velocity of fish u_f in respect to fluid field velocity u_w, M is the swimming mode related to the four fish behavior responses, *C* are drag coefficients, $\frac{dO}{dt}$ is the rate of exhaustion related to oxygen needed for each swimming mode, and P is swim thrust depending on the current direction θ of fish motion as:

$$P_x = P * \cos(\theta) \quad (2.5\text{-}6)$$

$$P_y = P * \sin(\theta) \quad (2.5\text{-}7)$$

Swim thrust *P* is calculated as:

$$P = \begin{cases} 0.5 C_f S_a \rho u_f^{\,2} & \\ S_p 0.5 C_f S_a \rho u_f^{\,2} & M = Sustained \\ (1.0 - \frac{1.0}{1.0 + |U_x|}) \frac{O}{O_{\max}} S_b A_R m_v & , \text{for} \quad M = \mathrm{Pr}olonged \\ & M = \mathrm{Re}verse \\ \frac{O}{O_{\max}} S_b A_B m_v & M = Burst \end{cases} \quad (2.5\text{-}8)$$

where, C_f is the drag coefficient for surface friction, S_a the wetted area of the fish, ρ is water density, u_f is fish swimming speed, $U_x = u_w - u_f$, A is the acceleration for each swimming mode, m_v is the virtual mass of the fish, S are factors depending on the species and O is the amount of time left for swimming modes, related to oxygen consumption.

Depending on the type of behavior response selected by the fish, there is a different oxygen consumption that is related to the time left for each swimming mode, which is measured by:

$$\frac{dO}{dt} = \begin{cases} 0.0 \\ -0.01f \\ -0.02f \\ -f \end{cases} \quad \text{, for} \quad \begin{matrix} M = Sustained \\ M = \mathrm{Pr}olonged \\ M = \mathrm{Re}verse \\ M = Burst \end{matrix} \qquad (2.5\text{-}9)$$

where, O is measured in units of time (s) with O=6s for every fish at the beginning of the simulation and f is nominally 1.0.

Fish behavior responses near the louvers are shown in Figure 7.1-1 and indicative fish paths simulated are shown in Figure 7.1-2.

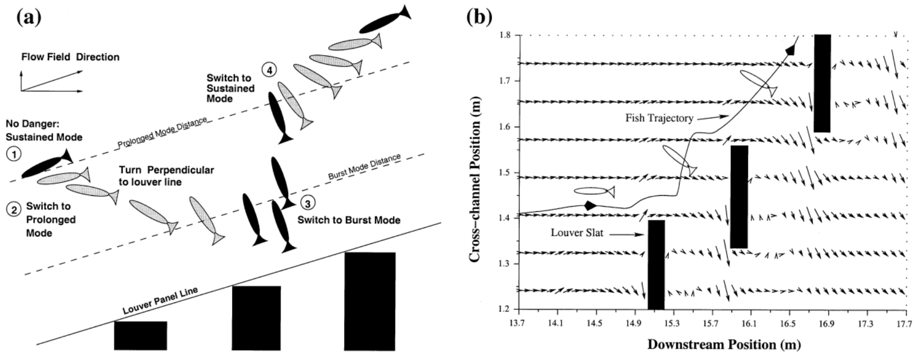


Figure 2.5-1: (a) Fish behaviour responses near the louvers (b) simulated fish path and flow field near the louvers [source: (Haefner and Bowen, 2002)]

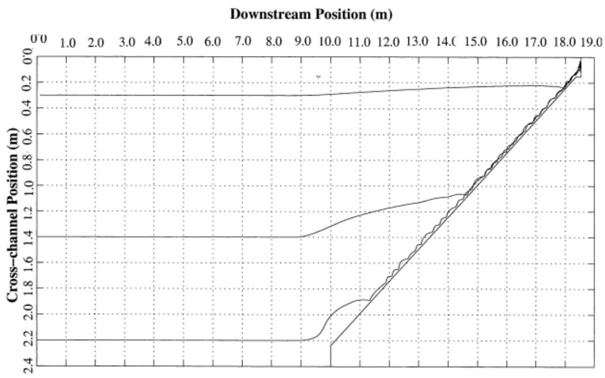


Figure 2.5-2: Simulated fish paths for different initial cross channel positions (0.3, 1.4, 2.2 m). The straight diagonal line is the louver panels [source: (Haefner and Bowen, 2002)]

Lemasson et al. (2008) modified the model of Haefner and Bowen (2002):

1. The behavioral rules already mentioned in 2.4.3 were added, and
2. an empirical derived relation between the rate of oxygen consumption and swimming speed was employed.

2.5.2 Goodwin et al. (2006); (2014)

Goodwin et al. presented two editions of his fish behavior model in the past decade. The main aspects of both models are:

1. CFD models solving the Reynolds averaged Navier-Stokes equations are used to calculate flow characteristics and used as inputs to the models,
2. the preferred computational mesh topology used is of multi-block near orthogonal structured meshes,
3. fish evaluate hydrodynamic stimuli inside their respective sensory ovoid as seen earlier to determine their behavior, and
4. when a behavior decision is determined, the respected fish swimming velocity vector (u_f, v_f, w_f) is assigned, by calculating speed and orientation for the selected behavior and fish location is updated as a relation to its previous position.

By using Weber's "just noticeable difference" each behavior is activated by recognizing a threshold excess between a signal of the respective stimulus and it's already acclimatized intensity expressed as:

$$E^t = \frac{I^t - {I_\alpha}^t}{{I_\alpha}^t} > k_i \qquad (2.5\text{-}10)$$

where, I^t is the intensity of the respective stimulus at the individual's position at time t, ${I_a}^t$ the value fish has adapted to (equation 2.4-1), and k_i the threshold associated with each behavior.

After determining which behavior is triggered, a probabilistic approach is used to simulate how fish switch from one behavior to another. An expected utility U^t is obtained by estimating a probability P^t of obtaining a utility, u_i assigned for each behavior. The adopted behavior is the one providing the maximum expected utility U^t as:

$${U_i}^t = {P_i}^t * u_i - {C_i}^t \qquad (2.5\text{-}11)$$

where, u_i the intrinsic utility for each behavior, ${P_i}^t$ the probability of each behavior utility and ${C_i}^t$ a bioenergetic cost for executing a behavior response.

After the fish swimming velocity vector (u_f, v_f, w_f) is assigned, fish location is updated as:

$$x^{t+dt} = x^t + (u + u_f) * \Delta t \qquad (2.5\text{-}12a)$$
$$y^{t+dt} = y^t + (v + v_f) * \Delta t \qquad (2.5\text{-}12b)$$
$$z^{t+dt} = z^t + (w + w_f) * \Delta t \qquad (2.5\text{-}12c)$$

where, (x, y, z) the position vector and (u, v, w) the flow velocity vector.

Goodwin et al. (2006) considered hydraulic strain as a stimulus for behavior decisions and, I^t, is dependent on the log of the hydraulic strain, scaled to a reference value, thus:

$$I^t = log \frac{S^t}{S_0} \qquad (2.5\text{-}13)$$

where, $S^t = \int \left| \partial u_i / \partial u_j \right|$ the hydraulic strain and S_0 a reference value.

Goodwin et al. (2014) used flow acceleration magnitude A_M as a stimulus, thus:

$$I^t = log \frac{A_M{}^t}{A_0} \qquad (2.5\text{-}14)$$

Both models considered vertical orientation as a separate behavior decision (B3), affected by hydrostatic pressure experienced by fish, and the already acclimatized depth (Goodwin et al., 2006; 2014). Swimming towards acclimatized depth (B3) as a behavior decision is triggered, when difference between fish elevation and depth fish is adapted to exceeds a threshold value k_3, thus:

$$E_3{}^t = \left|I_3{}^t - I_{a3}{}^t\right| > k_3 \qquad (2.5\text{-}15)$$

where, $I_3{}^t$ is perceived intensity of pressure stimulus at the individual's position at time t (i.e. the depth), $I_{a3}{}^t$ is perceived intensity of Pressure stimulus to which the individual has adapted to, also derived from (equation 2.4-1).

Indicative observed and modeled fish paths as well as flow field characteristics are shown in Figure 7.2-1.

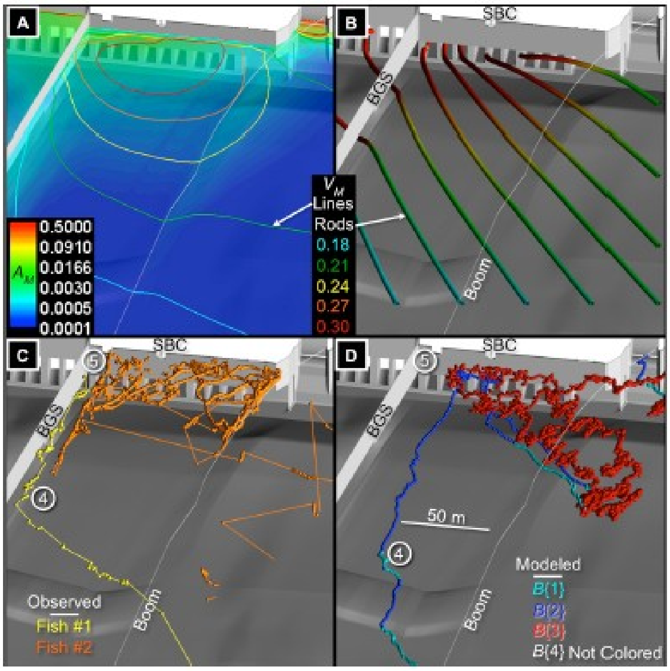


Figure 2.5-3: Flow field characteristics and fish paths. (a) contour lines of flow acceleration in simulation area, (b) flow velocity magnitude, (c) model-generated fish path, and (d) observed fish movement [source: (Goodwin et al. 2014)]

2.5.3 Arenas et al., 2015

Arenas et al. (2015) presented a study focused on the interplay between flow field acceleration and smolt swimming behavior, generating probability distributions for fish thrust and swimming direction (α in XY plane and θ_T in XZ plane) in respect to flow acceleration, as shown in Figure 2.5-4. Simulations and measurements were performed at the Rocky Reach Dam and Priest Rapids Dam of the Mid-Columbia River, (USA).

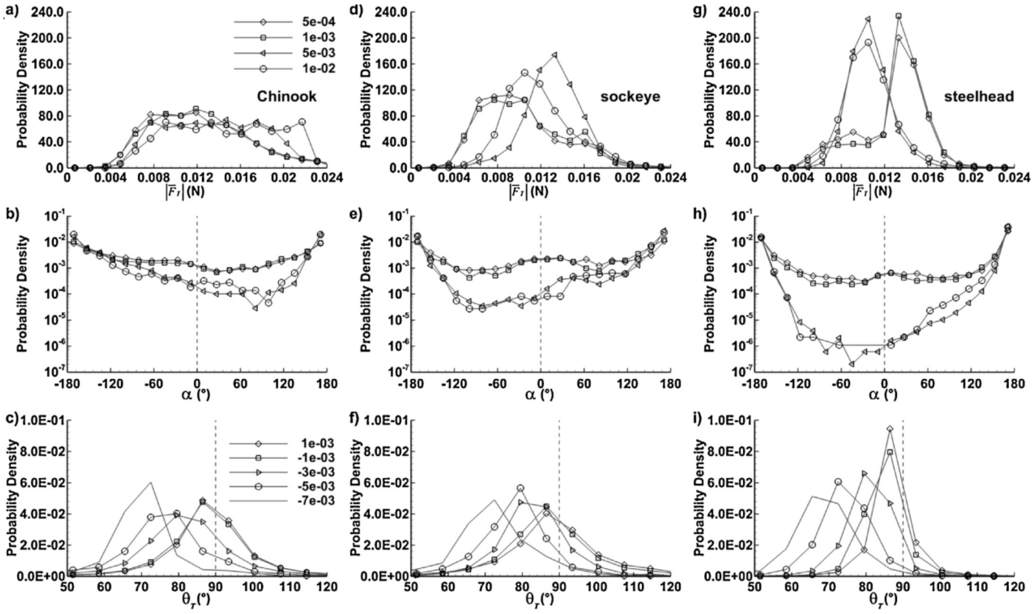


Figure 2.5-4: Probability distributions for fish thrust FT (first row), angle α (second row) and θ_T (third row) for three types of fish (a) to (c): Chinook salmon, (d) to (f): sockeye salmon and (g) to (i): steelhead [source: (Arenas et al., 2015)]

The main aspects of the study of Arenas et al. (2015) are:

1. CFD simulations were performed using ANSYS FLUENT to solve the Reynolds-Averaged Navier Stokes (RANS) equations and flow characteristics were calculated,
2. fish swim paths from data measurements were determined and shown in Figure 7.3-2 and 7.3-3,
3. newton's second law of motion was solved to find fish thrust at each measured location,
4. fish thrust components, fish orientation and swimming time were determined, and
5. probability distributions were generated for selected values of flow acceleration.

The following procedure was performed:

1. C_{df} was determined assuming fish was drifting (equation 2.5-18),
2. Drag force F_D, and fish thrust F_T was calculated using fish and ground velocity from measured data (equation 2.5-16, 2.5-17),
3. If $F_T<0.6\text{x}10^{-3}$ N then fish was drifting, and
4. If $F_T>0.6\text{x}10^{-3}$ N then the drag coefficient, and drag force were calculated for fish swimming, and fish thrust was calculated, also generating angles of fish orientation.

The following equations were used:

$$m_f \frac{d\vec{u}_g}{dt} = \vec{F}_D + \vec{F}_T \quad (2.5\text{-}16)$$

$$\vec{F}_D = -0.5\rho|\vec{u}_s|\vec{u}_s A C_{df} \quad (2.5\text{-}17)$$

where, $\vec{u}_g, m_f$ are the ground velocity and fish mass, $\vec{F}_T, \vec{F}_D$ are the fish trust and drag forces, $\vec{u}_s$ is the fish swim velocity, A is a reference area depending on the drag coefficient C_{df}:

$$C_{df} = \begin{cases} swim \begin{cases} \dfrac{493.9}{Re_f^{0.922}} \; if \; Re_f > 2000 \\ \dfrac{24}{Re_s}(1 + b_1 Re_s^{b2}) + \dfrac{b_3 Re_s}{b_4 + Re_s} \; if \; Re_f \le 2000 \end{cases} \\ drifting \left\{ \dfrac{0.072}{Re_f^{0.2}} \right. \end{cases} \quad (2.5\text{-}18)$$

where, $Re_f = \rho * |\vec{u}_s| * L/\mu$ is the fish Reynolds number and Re_s is the Reynolds number of a sphere with the same volume as the fish, and the coefficients:

$$\begin{aligned} b_1 &= \exp(2.3288 - 6.4581\gamma + 2.4486\gamma^2) \\ b_2 &= 0.0964 + 0.5565\gamma \\ b_3 &= \exp(4.905 - 13.8944\gamma + 18.4222\gamma^2 - 10.2599\gamma^3) \\ b_4 &= \exp(1.4681 + 12.2584\gamma - 20.7322\gamma^2 + 15.8855\gamma^3) \end{aligned} \quad (2.5\text{-}19)$$

where, $\gamma = s/S_f$ with s the surface area of a sphere with the same volume as the fish and S_f the actual surface of the fish.

In their 2015 work Arenas et al. used a coordinate transformation, relating fish orientation to the flow velocity, thus obtaining results independent of the definition of a Cartesian coordinate system. The angle between the vertical axis and fish thrust (same as fish-head orientation) is denoted as θ_T, between the vertical axis and flow velocity vector as θ_u. Changes in water depth is simulated by θ_T, with $\theta_T < 90^o$ representing fish swimming upwards and $\theta_T > 90^o$ swimming downwards. The angle between the projections of the thrust force and the flow velocity vector onto the XY plane is a, with $a = 0^o$ and $a = \pm 180^o$ denoting swimming in the same and opposite direction of the flow respectively, as shown in Figure 2.5-5.

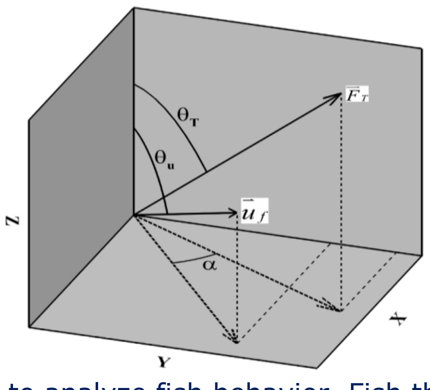


Figure 2.5-5: Angles used to analyze fish behavior. Fish thrust FT and flow velocity uf [source: (Arenas et al., 2015)]

3 PRESENTATION OF THE FISH BEHAVIOR MODEL

3.1 General

In this chapter, the role and main functions of the program created for simulating fish behavior are illustrated. Its purpose is to provide the reader with a general understanding of the program created. Following the main program structure, we analyze its various aspects and procedures necessary for the accurate simulation of the physical problem. This is done by decomposing the program into various chapters, highlighting on important information and providing the mathematical context associated with each procedure.

A flowchart (Chapter 3.3) is conducted, to facilitate the decoding process and clarify connections between various aspects of the program. The flowchart, acts as a tool for the reader to further understand the processes presented in chapter 3.2 and their necessity.

Finally, files associated with the program either as inputs (Chapter 3.4) or outputs (Chapter 3.5) are presented as they are essential to completion of the simulation.

The model created and the program presented below was based on the model proposed by Goodwin et al. (2014).

3.2 Description of the program

In order to follow the structure of the program and don't lose sight of different procedures, certain notations are used for characterizing each chapter and different process.

The main program is divided into 11 chapters, in accordance to their sequence of execution, to facilitate decoding.

3.2.1 Chapter 1-Preliminaries-read input data

In this chapter parameter and variable data is extracted from input files. The procedure is described in sections below.

Section 1.1: Read length and speed characteristics

The program reads coefficients related with fish speed and fish length, i.e. SPEEDCRU, SPEEDBOOST, SPEEDDRIF, SPEEDSUST and FISHLENG from file:

1. 'fish_charact.dat'.

Section 1.2: Read other fish characteristics

The program reads other coefficients necessary for the simulation, i.e. behavior coefficients, initial values of simulation parameters and fish initial position from files:

1. 'fish_BehavCoeff.txt'
2. 'sim_info_in.dat'
3. 'fish_location.txt'

3.2.2 Chapter 2-Read geometry from TELEMAC files and calculate accelerations

This Chapter consists of 4 sections.

Section 2.1: Initialization of variables.

Variables related to geometry and flow field values are initialized, i.e. X(I,J), Y(I,J), U(I,J), V(I,J).

Section 2.2: Read from TELEMAC files.

Geometry and flow field data are read from the TELEMAC files, i.e. variables X(I,J), Y(I,J), U(I,J), V(I,J),SURF(I,J) and BOT(I,J).

1. 'DATA_FISH_colums.txt'
2. 'DATA_BOTTOM.dat',
3. 'DATA_VELOCITY UV.dat', and
4. 'DATA_FREE SURFACE.dat'.

Thus, the coordinates, the velocity components and water elevations at all grid notes of the TELEMAC geometry are defined.

Section 2.3: Calculate Acceleration Magnitude (AccMg).

A new coordinate system (ksi,eta) is used to calculate the acceleration.

In order to calculate AccMg it is necessary to first find the velocity gradients $\frac{\partial U}{\partial x}$, $\frac{\partial U}{\partial y}$, $\frac{\partial V}{\partial x}$, and $\frac{\partial V}{\partial y}$ for every node of the simulation area. A new coordinate system (ksi,eta) is defined in order to calculate the velocity gradients for each node using finite differences. An appropriate interpolation scheme is then selected to apply the finite differences method. In the particular program, a linear interpolation scheme is selected. In particular for the interior nodes of the computational grid central differences are selected and for the boundary nodes upwind or downwind differencing scheme is selected. For both cases, a second order approximation is used. As an example, the interpolation scheme for $\frac{\partial U_i}{\partial x_j}$ is presented below.

Central differencing scheme for internal nodes,

$$\frac{\partial U_i}{\partial x} = \frac{U_{i+1} - U_{i-1}}{2 * DX} \tag{3.2-1}$$

Downwind differencing scheme for left boundary nodes,

$$\frac{\partial U_i}{\partial x} = \frac{-3 * U_i + 4 * U_{i+1} - U_{i+2}}{2 * DX} \tag{3.2-2}$$

Upwind differencing scheme for right boundary nodes,

$$\frac{\partial U_i}{\partial x} = \frac{+3 * U_i - 4 * U_{i-1} + U_{i-2}}{2 * DX} \tag{3.2-3}$$

$$AccMg = \sqrt{\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)^2+\left(U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)^2} \quad (3.2\text{-}4)$$

Section 2.4: Calculate perceived intensity of AccMg (IntAccMg) for plot

The intensity of the Acceleration magnitude is calculated, which corresponds to how fish perceives the acceleration magnitude, in order to create a plot file: 'toplotAccMgT.txt'.

$$IntAccMg = \log_{10}\frac{AccMg}{A0} \quad (3.2\text{-}5)$$

3.2.3 Chapter 3-Fish and Time loop for each fish

Section 3.1: Initialization of counters

Counters and variables necessary for the simulation are initialized, i.e. COUNTB1tot, countFB1, filenum and variables DX, FvelMgtot, XFold, YFold.

Section 3.2: Start of fish loop for a total number of fishes: FISHNUM

Fish iterations start from 1 to total number of fishes: FISHNUM.

Initial positions of the first 5 simulated fish are read from file: 'fish_location.txt' and written as outputs at files: 'FISH_POSITIONS01.txt' until 'FISH_POSITIONS05.txt'.

Counters COUNTB1, COUNTB2, COUNTB3 and fout are also initialized at the start of each fish iteration.

Section 3.3: Start of time loop for each fish, total number of iterations: ITERMAX

Time iterations start for each simulated fish and calculate the trajectory of each fish.

3.2.4 Chapter 4- Find the position of fish: IFISH,JFISH

In chapter 4 of the program a searching algorithm is used in order to find the location of the simulated fish in the computational grid. Fish location (XF, YF), which was imported earlier is used in order to check which node is located nearest to the fish. Thus, distances between fish location and all the grid nodes (I, J) are calculated. The node with the minimum distance is selected as seen in equation 3.2-5.

$$\text{IFISH} = \text{I},\ \text{JFISH} = \text{J} \quad (3.2\text{-}5)$$

It is noted that there is a possibility for fish to get off grid boundaries during the simulated movement, so a counter, *fout*, is used to indicate that the fish has escaped the grid after it encounters boundary nodes two consecutive times.

3.2.5 Chapter 5-Find the position of the Sensors: IXSEN (NSEN), IYSEN (YSEN)

Chapter 5 of the program is divided into three sections, in order to accurately simulate the fish Sensory Ovoid and its relation to the computational grid.

Section 5.1: Calculation of Sensor Distances

In this section the position of each sensory point is calculated in respect to the fish orientation.

As, a first step coefficients used in the simulation are set, i.e. NCOEFF, AM, A0, Coeff40 and DELTA (see Appendix).

As a second step the Sensory Query Distances (SQDs) are calculated, as the displacement from the location of the fish, with a procedure - that consists of Sensory Point Distance (SPDIST), Random Increase of sensory point distance (RINC) and stochastic noise to sensory point locations by Adding Range of variability to non-cardinal locations (RND) - illustrated below. The equation used can be found in the work of Goodwin et al. (2014).

$$SPDIST = \frac{NCOEFF}{\log_{10}(\frac{AccMg}{A0})} \quad (3.2\text{-}5)$$

$$RINC = 1 + RRSQD * DELTA \quad (3.2\text{-}6)$$

$$RND = (2 * RRSQD - 1) * Coeff40 \quad (3.2\text{-}7)$$

where, RRSQD is a random number of uniform distribution, ranging between 0 and 1, created for the Sensory Query Distances. A local coordinate system is used with coordinates (SQDX, SQDY), as shown in Figure 3.2-1 for each sensory point presented in Table 3.2-1.

Table 3.2-1: Sensory points coordinates in the local coordinate system, as distances from the fish center, also seen in Figure 3.2-1

Sensory point 1
SQDX(1) = 0
SQDY(1) = 0
Sensory point 2
SQDX(2) = SPDIST * RINC
SQDY(2) = SPDIST * RAND
Sensory point 3
SQDX(3) = -SPDIST * RINC
SQDY(3) = SPDIST * RAND
Sensory point 4
SQDX(4) = SPDIST * RAND
SQDY(4) = SPDIST * RINC
Sensory point 5
SQDX(5) = SPDIST * RAND
SQDY(5) = -SPDIST * RINC

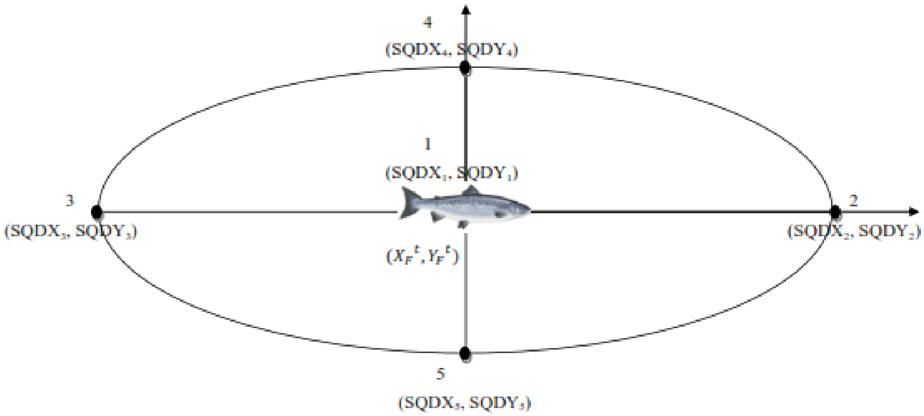


Figure 3.2-1: Representation of the 2D detection volume and the 5 sensory points. Point 1, is the center of the fish, points 2 and 3 are located in the direction of the fish head and tail respectively, and points 4 and 5 are located on the left and right side of the fish

Section 5.2: Calculation of sensor point coordinates in the global coordination system

The global (grid) coordinates of the sensory points are determined from the local SQDs. A rotation matrix is applied in the SQDs and added to the existing fish position, in order to find the boundaries of the Sensory Ovoid in grid coordinates (X, Y). The transformation procedure is depicted in equation 3.2-8 and 3.2-9.

$$\begin{Bmatrix} XSEN \\ YSEN \end{Bmatrix} = \begin{Bmatrix} XF \\ YF \end{Bmatrix} + R^{FISHANGXY} * \begin{Bmatrix} SQDx \\ SQDy \end{Bmatrix} \qquad (3.2\text{-}8)$$

The rotation matrix is given below:

$$R^{FISHANGXY} = \begin{bmatrix} \cos(FISHANGXY) & -\sin(FISHANGXY) \\ \sin(FISHANGXY) & \cos(FISHANGXY) \end{bmatrix} \qquad (3.2\text{-}9)$$

The matrix corresponds to the rotation of z-z axis with angle FISHANGXY.

Section 5.3: Calculation of sensor I and J in the global coordinate system

Similar to chapter 4, a sensory point position is requested in the computational grid, so a search algorithm is implemented, similar to the one used to identify fish position. Thus, the nodes of the grid are determined (IXSEN, IYSEN) for each sensory point, from where flow field information associated with the Sensory Ovoid is extracted.

3.2.6 Chapter 6- Decide Initial Behavior: Calculate DMETRIC and EVENT

From program chapter 5 starts the main part of the behavior decision making that affects fish movement. In this part fish extract hydrodynamic information through their Sensory Ovoid system, which was modeled earlier and start evaluating different behavior decisions based on that information that acts as stimuli.

Section 6.1: Calculation of flow velocities and angles

We extract the velocity components VELSEN(1,NSEN) , VELSEN(2,NSEN), and the acceleration magnitude ACCSEN(NSEN) for each sensory point from its grid location (IXSEN , IYSEN), so

$$\mathrm{VELSEN(1, NSEN) = U(IXSEN, IYSEN)},\qquad (3.2\text{-}10)$$

$$\mathrm{VELSEN(2, NSEN) = V(IXSEN, IYSEN)},\qquad (3.2\text{-}11)$$

$$\mathrm{ACCSEN(NSEN) = AccMg(IXSEN, IYSEN)}\qquad (3.2\text{-}12)$$

Having extracted necessary information about the flow field, flow characteristics needed for the simulation of the next move are given to the sensory points. The angle FLOWANGXY between the velocity vector and the computational grid is calculated for later use.

Section 6.2: Calculation of DMETRIC

The value of each behavior related stimulus is calculated, in order for the evaluation to continue using the given thresholds. Following the example by Goodwin et al. (2014), also seen in other relative literature (chapter 2.4 Locomotion, behavior responses and learning) basic behavior decisions that were modeled were:

1. B1-swimming with the flow,
2. B2-reacting-changing orientation towards faster flowing water, and
3. B3-retreating behavior by swimming against river flow.

For behavior B1, B2, B3 the perceived acceleration and acclimatized intensities are calculated (see Appendix):

$$IntAccPres = \log_{10}\frac{AccMg}{A0}\text{ , and}\qquad (3.2\text{-}13)$$

$$IntAccPast = (1 - MEMACCL) * IntAccPres + MEMACCL * IntAccPast\qquad (3.2\text{-}14)$$

The detection metric used as suggested by Goodwin et al. (2014) is calculated:

$$DMETRIC = \frac{IntAccPres - IntAccPast}{IntAccPast}\qquad (3.2\text{-}15)$$

It has to be noted that during first execution, $IntAccPres = IntAccPast$ and $IntAccPast \geq Coeff42$. Furthermore, $AccMg \geq 2*10^{-6}\,m/s^2$, acting as a lower bound for the perceived Acceleration Magnitude.

Section 6.3: Calculation of event

After finding for each behavior its respective intensity of stimulus, the detection metric found for each behavior is compared with the threshold values (THRES (1-3)). Detection Metrics for behaviors that exceed their respective thresholds are noted as EVENTS of possible behavior decisions (EVENT= 1).

3.2.7 Chapter 7- Calculate Probability and Utility of Behavior Decision

In this part, after having found which behavior decisions are active (possible decisions), a Utility Function is given for each behavior based on a probability of selecting each behavior. Finally the behavior with the greatest utility value for the fish is selected.

Section 7.1: Initialization of probabilities.

Probabilities PROB(:,:) are initialized for the first iteration and fish are assumed to have no previous preference (equal probabilities).

Section 7.2: Calculation of probabilities.

Probability of utility is then recalculated for each behavior decision as:

$$PROB = (1 - MEMBEH) * EVENT + MEMBEH * PROB^{past} \quad (3.2\text{-}16)$$

Section 7.3: Calculation of Utility for each decision

The Utility function is then calculated for each behavior (B1-B3) associating an intrinsic utility for each behavior, with the probability of obtaining this utility already found in the above procedure. This is done by:

$$UTIL = PROB * IntrUtil \quad (3.2\text{-}17)$$

Section 7.4: Calculation of Decision

For every time step the maximum Utility (UTILMAX), between behavior decisions B1, B2 and B3 is determined. The behavior decision associated with the maximum Utility function is selected, determining the subsequent swimming behavior. Swimming behavior decision is determined through a vector, named $NDECIS$, with values:

$$NDECIS^{t} = NDECIS^{t-1} + 1 \text{ , if } UTIL = UTILMAX \quad (3.2\text{-}18a)$$
$$NDECIS = 0 \text{ , if } UTIL < UTILMAX \quad (3.2\text{-}18b)$$

In equation 3.2-18a values greater than one indicate, that the fish selects the same swimming behavior decision more than once, and has selected it a number of NDECIS consecutive times.

Section 7.5: Calculation of counts

Counters related to behaviour decision are updated, e.g. COUNTB1, COUNTB1tot.

3.2.8 Chapter 8- Calculate velocity and angle

Having already determined which behavior decision the fish (agent) selects, NDESIC is given an appropriate value for each possible behavior. In chapter 8 the program checks which behavior response is triggered by examining for each behavior if equation 3.2-19 holds true. It then proceeds on calculating fish speed (SpeedFish) and change in angle (angleXY), in respect to its local coordinate system (where the fish's head is pointing).

$$NDECIS(i) \geq 1 \quad (3.2\text{-}19)$$

where, i=1,2,3 are the three modeled behaviors (B1, B2, B3).

Section 8.1: Behavior B1

If 3.2-19 holds true for i=1 then the fish (agent) has selected behavior B1 for its next move. When the agent switches to behavior B1 from another behavior it is assumed to orient itself to the flow. As a result the change in angle in respect to the local coordinate system is modeled as:

$$angleXY = FLOWANGXY - FISHANGXY \quad (3.2\text{-}20)$$

If the fish makes the decision of behavior B1 consecutive times, i.e. $NDECIS(i) > 1$ for i=1, then a Random Walk is implemented, biased towards the direction of the main flow. The modeled fish moves within an angle ±20° in the XY plane as seen in equation 3.2-21.

$$angleXY = RRB1 * 20^o \text{ , if } NDECIS = 2 \quad (3.2\text{-}21a)$$

$$angleXY = RRB1 * 20^o + angleXY \text{ , if } NDECIS(1) > 2 \quad (3.2\text{-}21b)$$

where, $RRB1$ implementing a Random Range in Direction.

Equation 3.2-21 is valid until:

$$R1 \leq e^{0.005*(NDECIS(1)-1)} - 1 \text{ (=TOPANG)} \quad (3.2\text{-}22)$$

where, R1 is a random number from a uniform distribution, of range between 0 and 1.

The speed in which the agent moves to its new direction is calculated using different classes of swimming speeds, as seen in Chapter 2.4. By including a random number from a uniform distribution RR, ranging between -0.5 and 0.5, as a Random Range of Speed Increase, the agents speed is:

$$SPEEDFISH = FISHLENG * (SPEEDCRU + RR * (SPEEDCRU - SPEEDDRIF) \quad (3.2\text{-}23)$$

Section 8.2: Behavior B3

The state B3 (swim against flow vector), is an escape response. When the agent switches to behavior B3 from another behavior it is assumed to orient against the flow. As a result the change in angle in respect to the local coordinate system is modeled as:

$$angleXY = FLOWANGXY - FISHANGXY - 180 \quad (3.2\text{-}24)$$

Subsequent moves occur with orientation against the flow vector within an angle:

$$angleXY = 180 / \log(AccMg / A0) - FLOWANGXY \quad (3.2\text{-}25)$$

Where persistent change as shown in (3.2-25) perpetuates unless fish angle exceeds angleXY=±90° or (3.2-22) is true. Swim speed upon transition to B3 is equal to:

$$SPEEDFISH = FISHLENG * SPEEDBOOST \quad (3.2\text{-}26)$$

and decays if the B3 behavior is selected in subsequent time steps as shown in (3.2-27) but does not drop below (3.2-23) and it is further bounded by $[S_{Cruise}, S_{Boost}]$.

$$SPEEDFISH = SPEEDFISH * (1 - 0.025) \quad (3.12\text{-}27)$$

Section 8.3: Behavior B2

If 3.2-19 holds true for i=2 then the fish (agent) has selected behavior B2 for its next move. In behavior B2 the fish is modeled to receive information regarding the velocity magnitude of the surrounding flow and changes its movement speed and orientation to accommodate faster flowing water. Information of water velocities for every Sensory Ovoid point is stored to find the maximum velocity magnitude inside its perception Ovoid. Thus, the following arrays are created:

B2behav(NSEN) = 1. / FLOWVEL (NSEN) (3.2-28)

Where NSEN = 1, 2, 3, 4, 5 the locations of the Sensory Ovoid from where velocity information is extracted.

The program then finds the minimum or number of minimum of the B2behav(NSEN) array for and selects to change direction, where B2behav is minimum. After selecting main direction a random change from the main angle is implemented as in (3.2-21):

$$angleXY = angleXY + RRB2 * 20^o \quad (3.2\text{-}29)$$

For behavior B2 when the fish reduces water acceleration A_M in successive time steps, swim speed SPEEDFISH is set in the same manner as in (3.2-21b). If not, then speed boosts as:

$$SPEEDFISH = FLOWVEL(1) * (1 + 1.5) \quad (3.2\text{-}30)$$

Where, FLOWVEL is water velocity magnitude and 1.5 is the boost, with $SPEEDFISH$ bounded by $[S_{Cruise}, S_{Boost}]$, as entered in Input 1.2 (SPEEDCRU, SPEEDBOOST).

3.2.9 Chapter 9- Calculate Velocity Components

At program chapter 9 swim speed and direction of the next move for the modeled fish is converted into a velocity vector FISHVELXYZ(1-2) so as its movement can be simulated. Initially fish velocity vector is found in respect to the local coordinate system, which is relative to fish orientation. The program then uses a rotation matrix similar to the one used to find the fish Sensory Ovoid system using (3.2-8 and 3.2-9).

$$\begin{Bmatrix} \text{FISHVELXYZ(1)} \\ \text{FISHVELXYZ(2)} \end{Bmatrix} = \begin{Bmatrix} \text{FISHVELnew(1)} \\ \text{FISHVELnew(2)} \end{Bmatrix} * R^{\text{FISHANGXY}} \quad (3.2\text{-}30)$$

where FISHVELnew(1-2) is the components of SPEEDFISH regarding angleXY and

$$R^{\text{FISHANGXY}} = \begin{Bmatrix} \cos(\text{FISHANGXY}) & -\sin(\text{FISHANGXY}) \\ \sin(\text{FISHANGXY}) & \cos(\text{FISHANGXY}) \end{Bmatrix} \quad (3.2\text{-}31)$$

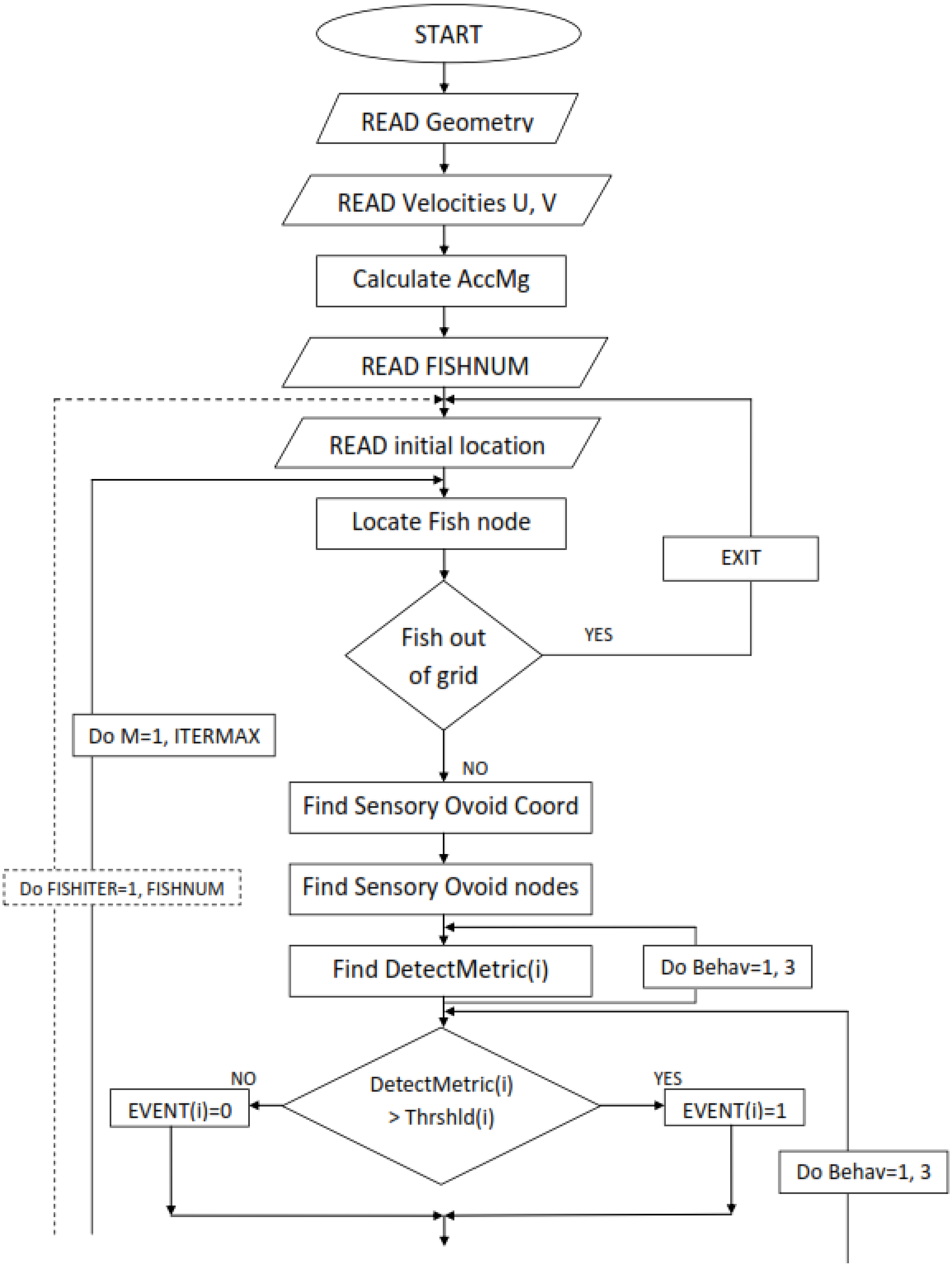
3.2.10 Chapter 10- Update and write fish paths

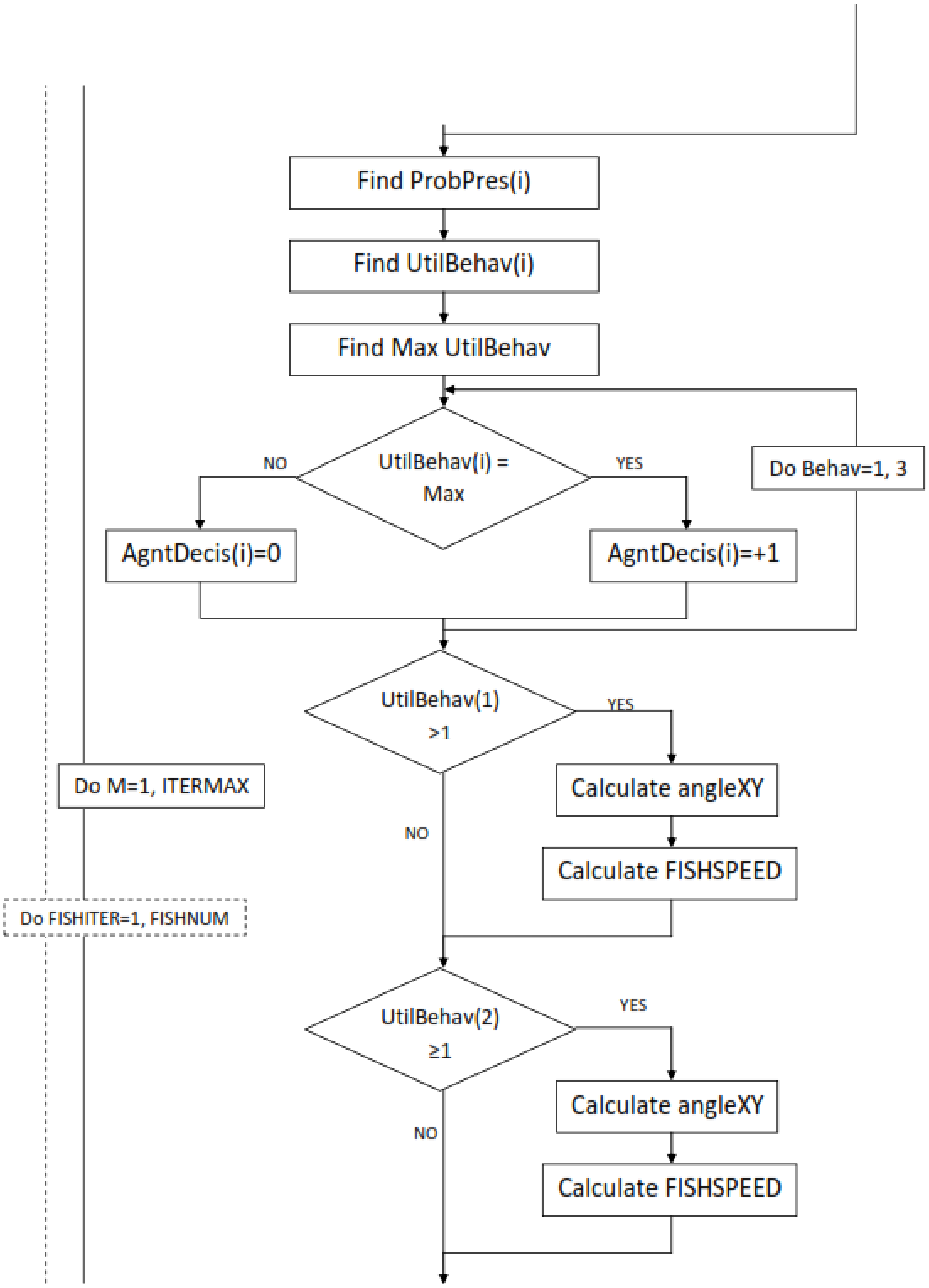
At program chapter 10 the modeled fish's location and simulation time are updated for the next iteration. Fish location, set in global CFD coordinates from the previous procedure, is updated using the equations of motion, as described in (2.5-12). The program also checks if the fish has reached an open boundary and should stop the computation. The displacement is calculated in this time step and in total. Fish orientation on the XY-plane is also updated and results are printed on an output file: "FISH_POSITIONS01.txt".

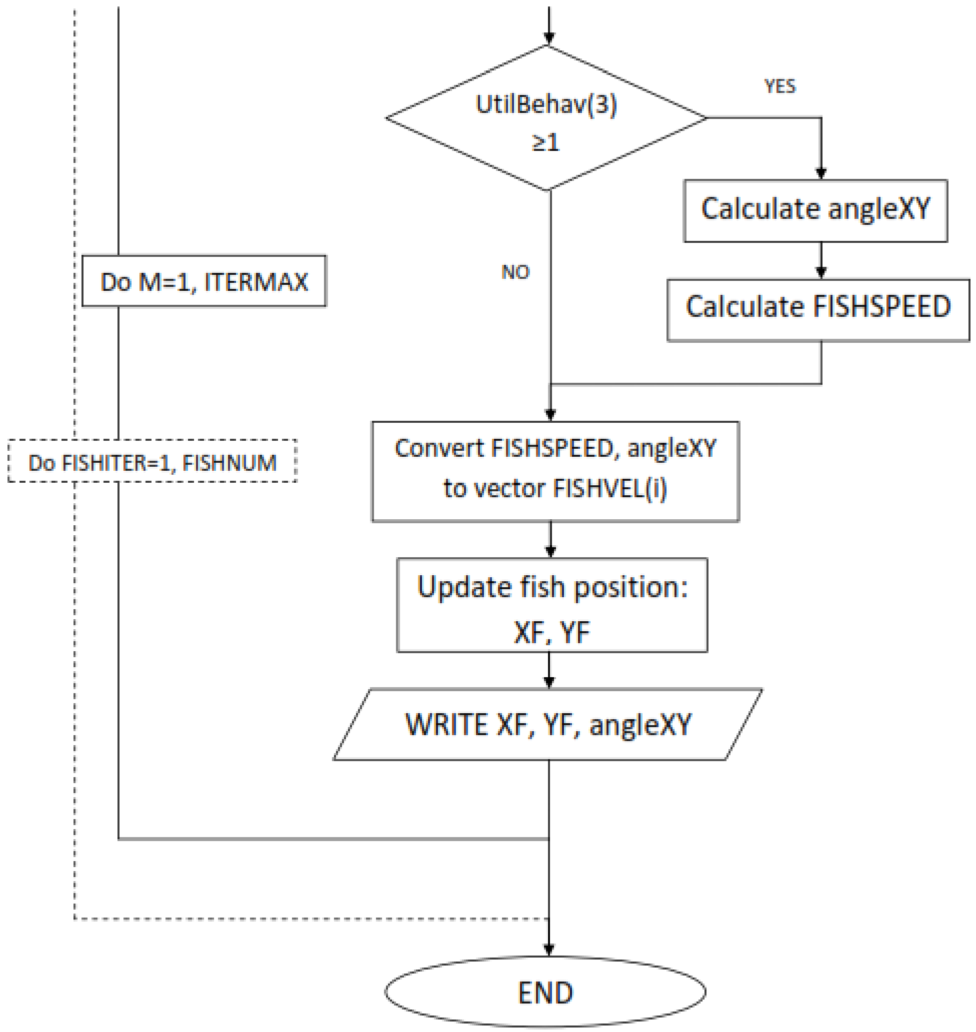
3.2.11 Chapter 11- End of fish loop for the current (one) fish

At the final chapter 11 of the program, we exit fish loop after maximum number of iterations, and several messages are printed to the user, presenting the progress of the computation. Finally in case of multiple fish simulations, variables related to individual fish behavior and iteration count are re-initialized for the next fish simulation.

3.3 Flowchart




Find ProbPres(i)
Find UtilBehav(i)
Find Max UtilBehav
UtilBehav(i) = Max
NO
YES
Do Behav=1, 3
AgntDecis(i)=0
AgntDecis(i)=+1
UtilBehav(1) >1
YES
Do M=1, ITERMAX
Calculate angleXY
NO
Calculate FISHSPEED
Do FISHITER=1, FISHNUM
UtilBehav(2) ≥1
YES
Calculate angleXY
NO
Calculate FISHSPEED

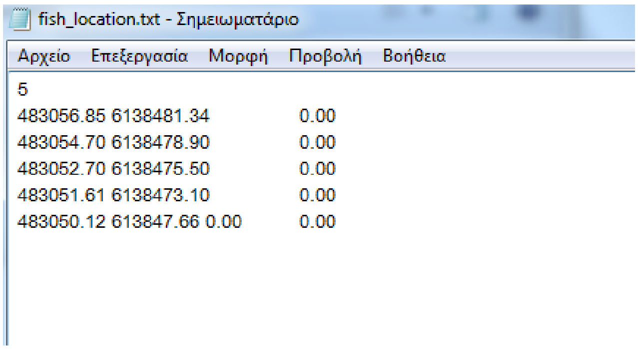

UtilBehav(3)
≥1
YES
NO
Calculate angleXY
Calculate FISHSPEED
Do M=1, ITERMAX
Do FISHITER=1, FISHNUM
Convert FISHSPEED, angleXY
to vector FISHVEL(i)
Update fish position:
XF, YF
WRITE XF, YF, angleXY
END

3.4 Input files

Input files for the fish behavior model include several files with different roles. Those, essential to completion of the simulation, are presented in this section. Data depicted in figures below are extracted from the application presented in the next chapter.

Input file: "fish_location.txt":

Lists the xy-positions where each fish will start, i.e. the fish release locations, and their original orientation related to the CFD grid. Additionally, the first number indicates the number of fish to be simulated, and whose initial information are given.



fish_location.txt - Σημειωματάριο

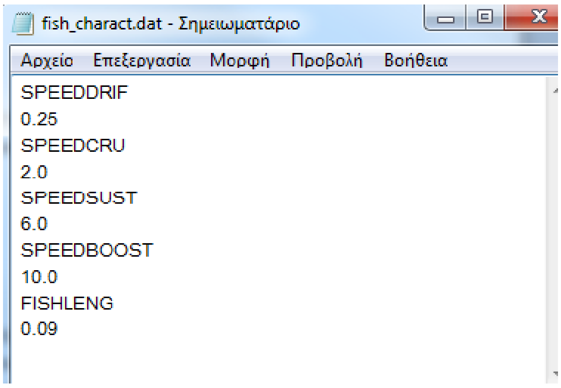
Αρχείο Επεξεργασία Μορφή Προβολή Βοήθεια

```
5
483056.85 6138481.34        0.00
483054.70 6138478.90        0.00
483052.70 6138475.50        0.00
483051.61 6138473.10        0.00
483050.12 613847.66 0.00    0.00
```

Figure 4.3-1: Fish release location file

Input file "fish_charact.dat":

Lists the swim speed coefficients, which will be multiplied with the fish length to calculate swim speed. Fish length is also provided in this file.



fish_charact.dat - Σημειωματάριο

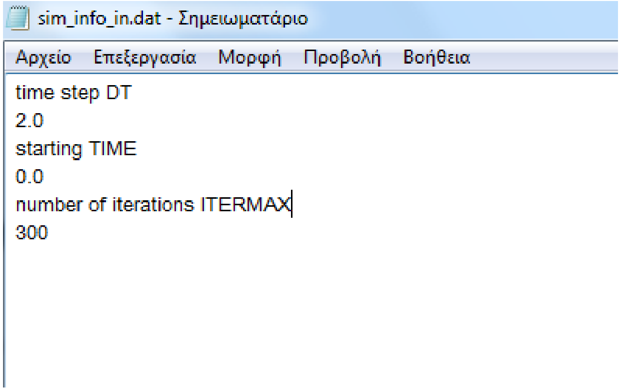
Αρχείο Επεξεργασία Μορφή Προβολή Βοήθεια

```
SPEEDDRIF
0.25
SPEEDCRU
2.0
SPEEDSUST
6.0
SPEEDBOOST
10.0
FISHLENG
0.09
```

Figure 3.4-2: Fish swim characteristics file

Input file "sim_info_in.dat":

Provides with the basic simulation information: time step (DT), initial time at the start of iterations (TIME), and number of iterations (ITERMAX).



sim_info_in.dat - Σημειωματάριο

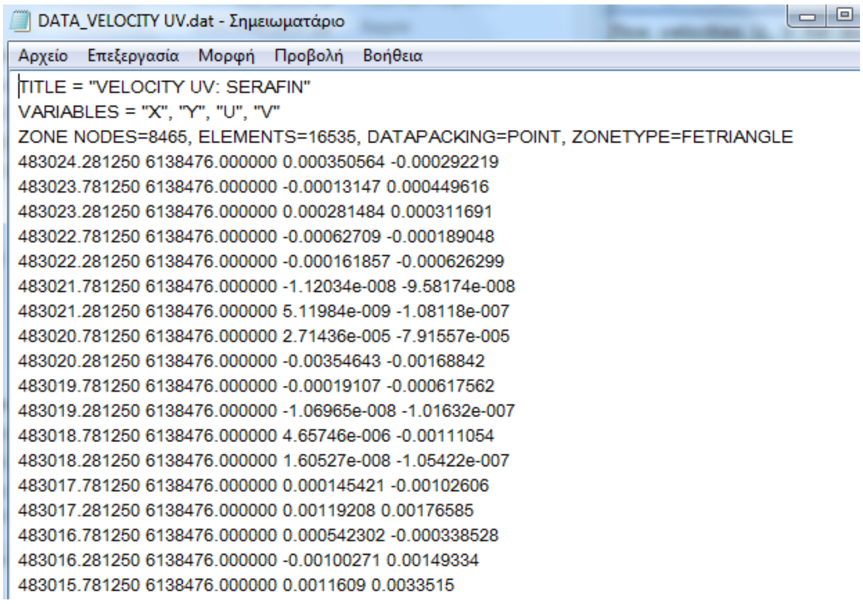
Αρχείο Επεξεργασία Μορφή Προβολή Βοήθεια

```
time step DT
2.0
starting TIME
0.0
number of iterations ITERMAX
300
```

Figure 3.4-3: Simulation information file

Input file "DATA_VELOCITY UV.dat":

Provides with the flow field information, and in particular flow velocities U, V for every node with coordinates X, Y of the computational grid.



DATA_VELOCITY UV.dat - Σημειωματάριο

Αρχείο Επεξεργασία Μορφή Προβολή Βοήθεια

```
TITLE = "VELOCITY UV: SERAFIN"
VARIABLES = "X", "Y", "U", "V"
ZONE NODES=8465, ELEMENTS=16535, DATAPACKING=POINT, ZONETYPE=FETRIANGLE
483024.281250 6138476.000000 0.000350564 -0.000292219
483023.781250 6138476.000000 -0.00013147 0.000449616
483023.281250 6138476.000000 0.000281484 0.000311691
483022.781250 6138476.000000 -0.00062709 -0.000189048
483022.281250 6138476.000000 -0.000161857 -0.000626299
483021.781250 6138476.000000 -1.12034e-008 -9.58174e-008
483021.281250 6138476.000000 5.11984e-009 -1.08118e-007
483020.781250 6138476.000000 2.71436e-005 -7.91557e-005
483020.281250 6138476.000000 -0.00354643 -0.00168842
483019.781250 6138476.000000 -0.00019107 -0.000617562
483019.281250 6138476.000000 -1.06965e-008 -1.01632e-007
483018.781250 6138476.000000 4.65746e-006 -0.00111054
483018.281250 6138476.000000 1.60527e-008 -1.05422e-007
483017.781250 6138476.000000 0.000145421 -0.00102606
483017.281250 6138476.000000 0.00119208 0.00176585
483016.781250 6138476.000000 0.000542302 -0.000338528
483016.281250 6138476.000000 -0.00100271 0.00149334
483015.781250 6138476.000000 0.0011609 0.0033515
```

Figure 3.4-4: Flow field information file

<u>Input file "fishBehavCoeff.txt":</u>

In this file, all sensory and behavior coefficients are enclosed. It consists of 9 coefficients, necessary for the calculation of simulating fish behavior responses.

```
fish_BehavCoeff.txt - Σημειωματάριο
Αρχείο  Επεξεργασία  Μορφή  Προβολή  Βοήθεια
#Thrshld(1)
0.
#Thrshld(2)
0.13
#Thrshld(3)
0.89
#ACCzeroRef
1.E-6
#MemCoefAccl(2)
0.999
#MemCoefAccl(3)
0.95
MemCoefBehav(1)
1.
MemCoefBehav(2)
0.0
MemCoefBehav(3)
0.998
IntrUtil(1)
1.
IntrUtil(2)
0.5
IntrUtil(3)
1.
```

Figure 3.4-5: Fish behavior coefficients

3.5 Output files

Output files from the present model summarize the results from the movement simulation and present fish positions in the CFD grid throughout the computation period.

<u>Output file "FISH_POSITIONS%.txt":</u>

In this file fish positions are presented, using their coordinates and orientation for each iteration of the computation. A separate file for each simulated fish is printed limited by 100 modeled fish.

```
FISH_POSITIONS01.txt - Σημειωματάριο
Αρχείο  Επεξεργασία  Μορφή  Προβολή  Βοήθεια
#XF   YF   TIME
 483014.400000000000000  6138489.960000000000000  0.000000000000000E+000
 483013.167621021600000  6138490.389682394000000   2.000000000000000
 483012.312740193800000  6138490.860593698000000   4.000000000000000
 483011.389886982800000  6138491.427809244000000   6.000000000000000
 483010.428455017300000  6138491.868964039000000   8.000000000000000
 483009.092424255400000  6138491.904148900000000  10.000000000000000
 483008.082496450800000  6138491.580820002000000  12.000000000000000
 483007.556804474100000  6138490.733548468000000  14.000000000000000
 483007.538778474500000  6138490.205489206000000  16.000000000000000
 483008.069970689300000  6138489.853207296000000  18.000000000000000
 483008.251341903200000  6138490.053868429000000  20.000000000000000
 483007.028210818200000  6138490.530441823000000  22.000000000000000
 483006.217346869900000  6138490.850685235000000  24.000000000000000
 483005.386994832100000  6138491.066181175000000  26.000000000000000
 483004.461759769800000  6138491.140422558000000  28.000000000000000
 483003.120058650300000  6138490.986494743000000  30.000000000000000
 483002.202500738000000  6138490.967655817000000  32.000000000000000
 483001.392136265900000  6138491.153175957000000  34.000000000000000
 483000.616471709300000  6138491.794073390000000  36.000000000000000
 482999.906478089900000  6138492.060780999000000  38.000000000000000
 482999.134332298100000  6138492.360425958000000  40.000000000000000
 482997.864830192500000  6138492.501583711000000  42.000000000000000
 482996.826089576900000  6138492.862407446000000  44.000000000000000
 482995.985847471200000  6138493.540371418000000  46.000000000000000
 482995.633574263900000  6138494.226778711000000  48.000000000000000
 482995.953160486300000  6138494.923159618000000  50.000000000000000
```

Figure 3.5-1: Fish position information file

4 CASE STUDY: JEDSTED MILL FISH FARM

4.1 Case study area – Jedsted Mill Fish Farm

For the calibration and validation of the proposed fish behavior model it was necessary to determine an area for which there have been studies concerning fish movement during downstream migration and relative data could be found. Information about water velocities, bathymetry data and discharge was also necessary. For the present application the Konge River was selected as a study case, located in western Denmark, and more specifically the area of the Jedsted Mill Fish Farm, for which there have been studies and data of fish trajectories (Svendsen et al. 2010; 2011).

Figure 4.1-1: Area of interest: Jedsted Mill Fish Farm

General characteristics of the Konge River can be found in Table 4.1-1 and further information concerning the Jedsted Mill Fish Farm in Table 4.1-2.

Table 4.1-1: General information for the Konge River [Source: (Svendsen et al. 2011)]

Konge River general information		
Location	Western Denmark	drains into Wadden Sea
Average slope	0.05	%
Mean annual discharge	7	m^3/s
River width	8÷15	m
Depth	0.5÷1.4	m
Substrate	sand interspersed with scattered areas of gravel	

Table 4.1-2: General information for the Jedsted Mill Fish Farm [Source: (Svendsen et al. 2011)]

Jedsted Mill Fish Farm area information		
Location:	Coordinates:	55◦ 23 N; 8◦ 43 E
	7 km upstream of Wadden Sea	
	90 m upstream of standard sharp-crested weir	
Discharge	Controlled by weir of Height=2m	
Slope	0.034	%

In the area of interest, water is diverted from the river into the fish farm and fish have been found to abandon downstream migration and enter the fish farm depending on the discharge allocated to the facility. During the fish tracking experiments total stream discharge and discharge diverted to the Jedsted Mill Fish Farm was measured as can be seen in Table 4.1-3.

Table 4.1-3: Discharge information for the fish tracking study period [Source: (Svendsen et al. 2010)]

Jedsted Mill Fish Farm - Case study		
Total stream discharge	2.66±0.37	m^3/s
Discharge diverted to fish farm	20±6.7	%
Free Surface Elevation	2	m
Slope	0.034	%

The substrate for the Konge River in the area of interest was also determined in order to obtain roughness coefficients for simulating river flow. The river bed is comprised mainly by silt and sand, being muddy near the edges. Furthermore when the Atlantic Salmon were tracked, vegetation of the river was dense, comprised of Spargarium emersum, as shown in Figure 4.2-4, with 50% coverage (Dr. Jon C. Svendsen, personal communication).

Figure 4.1-2: Vegetation in simulation area for calculation of Manning coefficient

After contacting the author of the scientific paper "Linking individual behavior and migration success in *Salmo salar* smolts approaching a water withdrawal site: implications for management", Dr. Jon C. Svendsen, researcher at the DTU, he provided us with bathymetry and current velocity data for the area of interest, as well as data of fish trajectories for the same area. Using this information a simulation of the river flow was possible, from which necessary hydrodynamic information for the fish behavior model can be acquired.

4.2 Measurements of fish trajectories for the Jedsted Mill Fish Farm

Measurements for the fish trajectories data were done during downstream migration in the area of interest. Fish characteristics can be seen in Table 4.2-1.

Table 4.2-1: Characteristics of measured fish for the Jedsted Mill Fish Farm [Source: (Svendsen et al., 2011)]

Fish information		
Fish type	wild Atlantic smolts (*Salmo Salar*)	
Average Fish Length	19.1±1.1	cm
Body mass	53.1±9.9	g
Release period	during spring	darkness (≥2h after sunset)

Fish data provided to us were derived of a Data.7z file containing 57 files '.txt' with measured fish positions at each time moment.

Table 4.2-2: Data of fish measurements [Source: (Dr. Jon C. Svendsen, after personal communication]

*TxTime (s)	Tag	X (m)	Y (m)
40036129.00	1970	6232605.93	1390327.14
40532615.00	1970	6232594.23	1390325.80
40556255.00	1970	6232590.10	1390325.64
40579895.00	1970	6232587.14	1390325.69
40603536.00	1970	6232584.99	1390325.93
40627179.00	1970	6232583.39	1390326.31
40650823.00	1970	6232582.25	1390326.70

1. Column TxTime: Time stamp for each measured fish coordinate, which can be calculated by the difference of the first 'TxTime' value and the one examined, divided by 12000. Thus the total time in seconds can be derived (e.g. Time=40556255-40532615)/12000=1.97s).
2. Column Tag: Refers to each measured fish (Identity code number).
3. Column X, Y: Coordinates of tagged fish for every time step.

The X, Y coordinates of the hydrophone receivers used for measuring fish location were also given as supplementary data and are presented in Table 4.3-3.

Table 4.2-3: X, Y coordinates of the hydrophone receivers used for measuring fish location [Source: (Dr. Jon C. Svendsen, after personal communication]

	X	Y	units
Hydrophone 1:	6232566.49	1390317.40	(m)
Hydrophone 2:	6232588.90	1390330.45	
Hydrophone 3:	6232564.51	1390297.65	
Hydrophone 4:	6232603.07	1390319.99	

Presentation of fish paths from measurements in the case study area

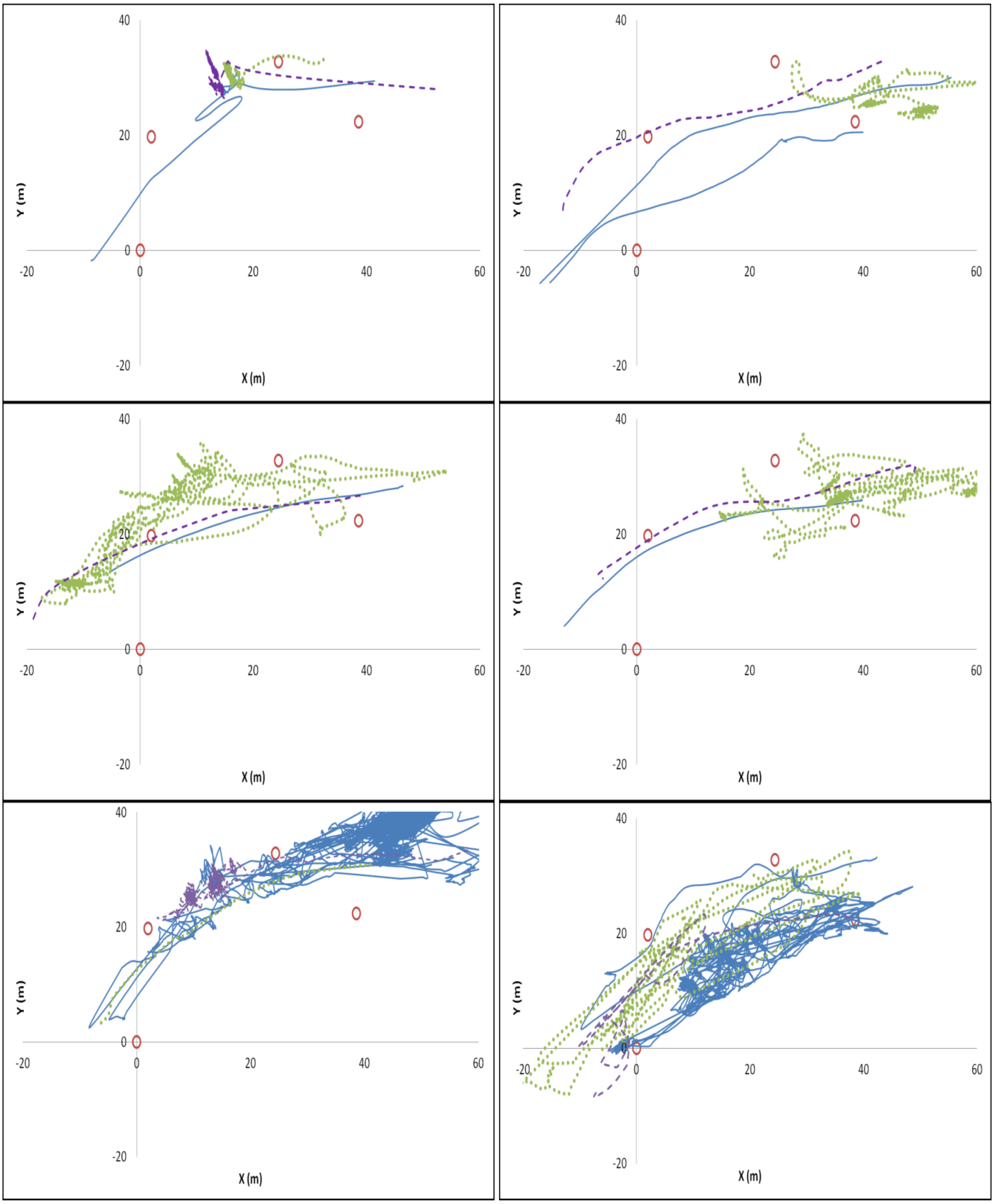


Figure 4.2-1(a): Fish paths (fish 1 through 18) as measured in the Jedsted Mill Fish Farm. The red circle points represent the position of the 4 hydrophones used for tracking fish paths

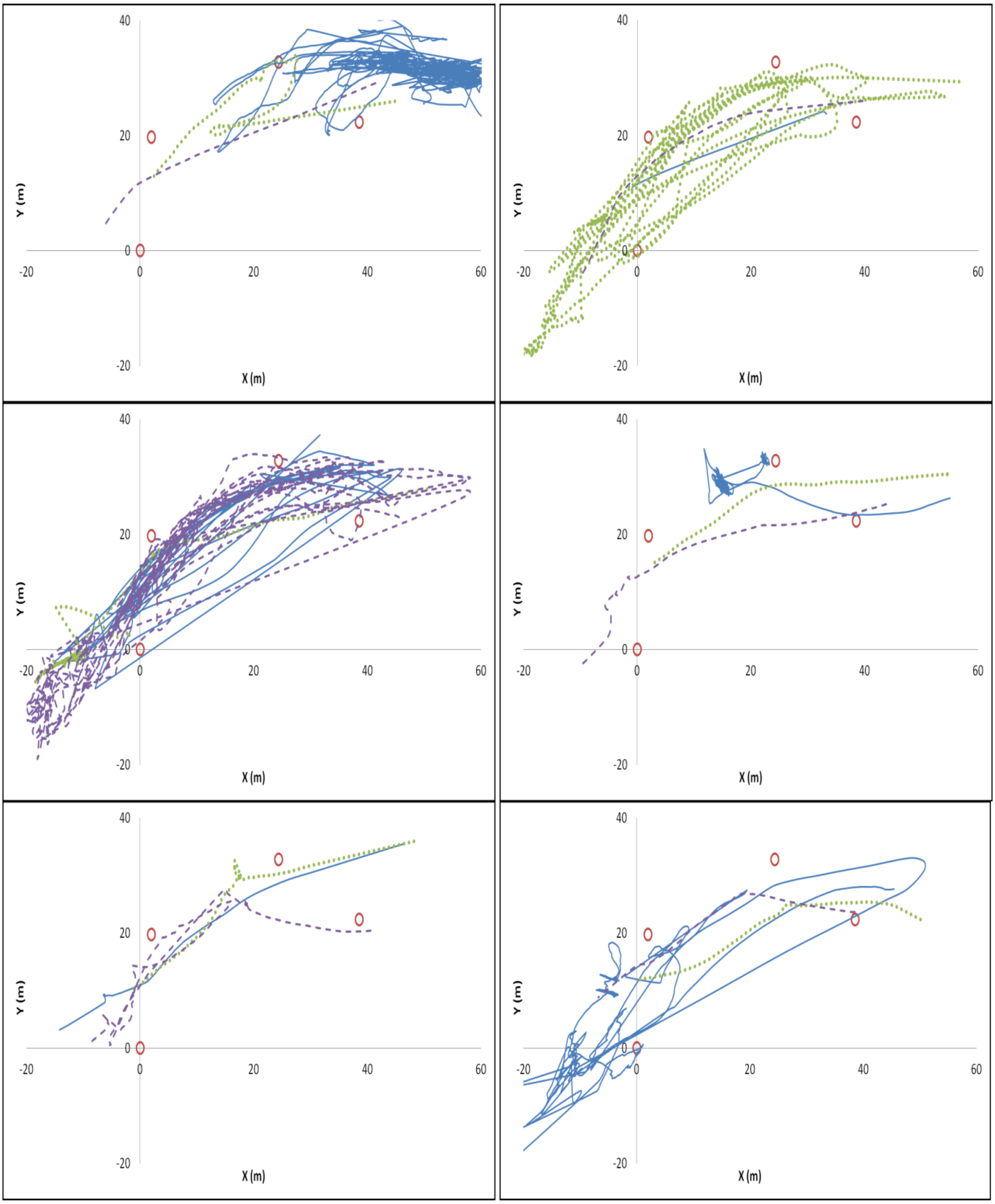


Figure 4.2-1(b): Fish paths (fish 19 through 36) as measured in the Jedsted Mill Fish Farm. The red circle points represent the position of the 4 hydrophones used for tracking fish paths

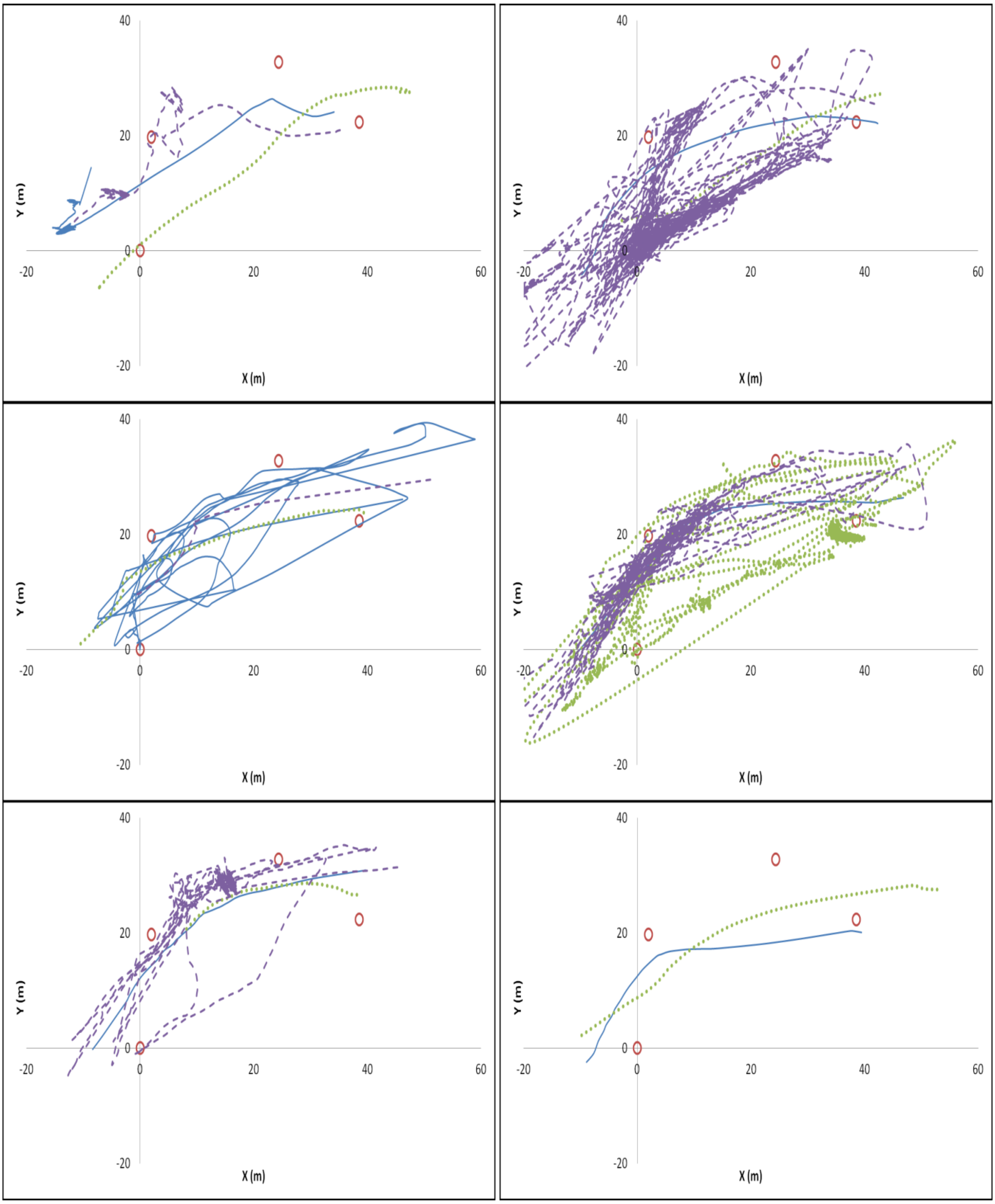


Figure 4.2-1(c): Fish paths (fish 37 through 54) as measured in the Jedsted Mill Fish Farm. The red circle points represent the position of the 4 hydrophones used for tracking fish paths

4.3 Bathymetry and velocity data, discharge and riverbed roughness information

4.3.1 Bathymetry data and depth average velocities

For the area of interest we were provided with GIS data in the form of water depth and average velocity contour lines for the Jedsted Mill Fish Farm area as shown in Figure 4.3-1 and Figure 4.3-2.

Figure 4.3-1: Contour lines of water depth in the area of Jedsted Mill Fish Farm. Cross sections at the inflow and outflow location are shown with white straight lines [Source: (Jon C. Svendsen, after personal communication]

Figure 4.3-2: Contour lines of depth average velocities in the area of Jedsted Mill Fish Farm. Cross sections at the inflow and outflow location are shown with white straight lines [Source: (Jon C. Svendsen, after personal communication]

4.3.2 Calculation of Discharge for the case study area

Using the data provided cross sections for the inflow and outflow were constructed in order to calculate the discharge at the boundaries of the area. Specifically, cross section were drawn at the upstream part of the area (Cross_Section_1), at the area that water is diverted to the Jedsted Mill Fish Farm (Cross_Section_2), and at the downstream (Cross_Section_3).

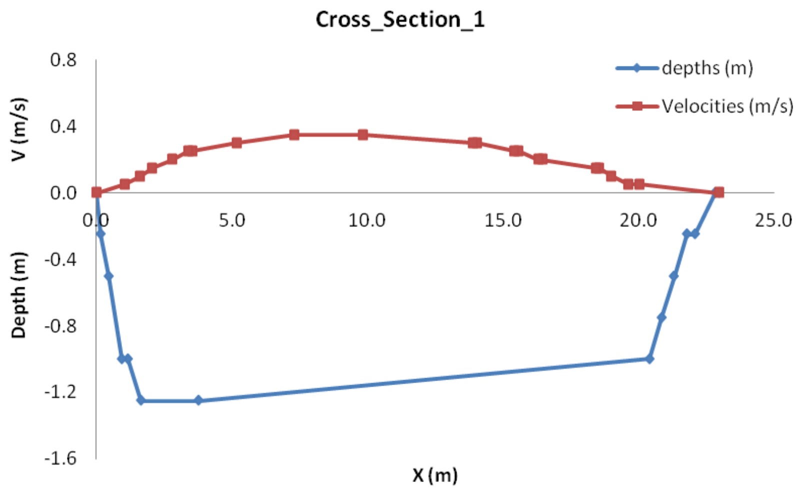


Figure 4.3-3: Water depths and average velocity at Cross_Section_1 (intake)

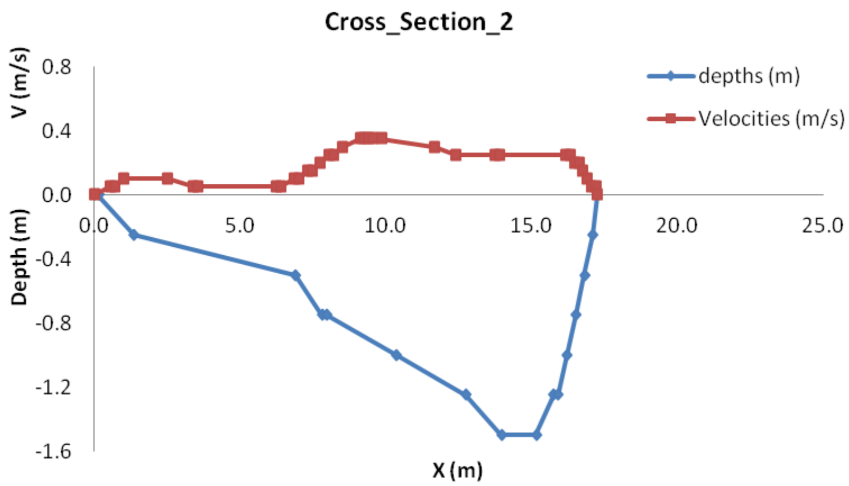


Figure 4.3-4: Water depths and average velocity at Cross_Section_2 (water diversion to Jedsted Mill Fish Farm)

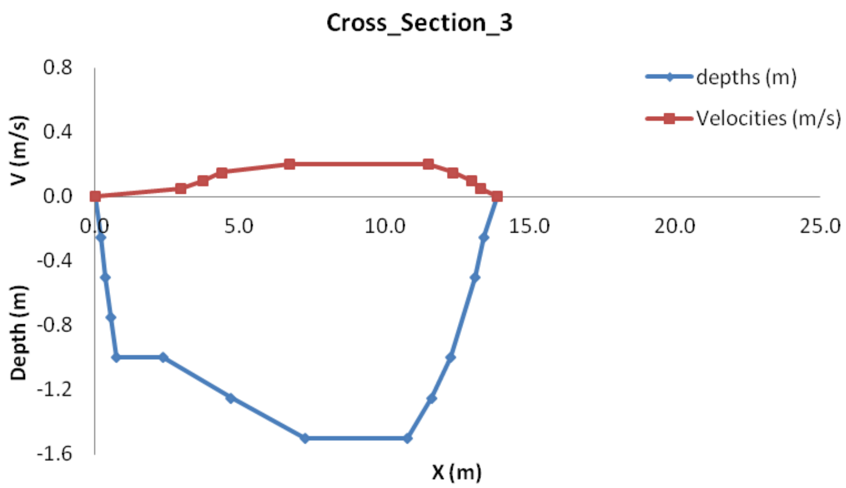


Figure 4.3-5: Water depths and average velocity at Cross_Section_3 (downstream outflow)

Having as data water depths and depth average water velocities, discharge was calculated for the different Cross Sections. Calculated discharges presented an error of 2% which is considered acceptable. Errors up to 5-8% are considered acceptable and can be attributed to human error during measurements or error of the given equipment.

Table 4.3-1: Discharge calculated at cross sections Δ1, Δ2, Δ3

Cross Section	Discharge	units
Cross_Section-1	5.66	m^3/s
Cross_Section-2	2.95	
Cross_Section-3	2.6	

It has to be noted that the vathymetry, velocity and discharge information provided, do not correspond to the time of fish downstream migration. In order to accurately simulate the flow field during the time of the case study, the hydrodynamic flow field needs to be first structured and calibrated, using the above information. The hydrodynamic model can then be utilized to simulate water flow conditions during measurements of fish trajectories (Table 4.1-3).

4.3.3 Riverbed data and roughness coefficients

In order to simulate roughness of the riverbed, Manning's equation was used, according to which:

$$V = \frac{1}{n} R^{2/3} J^{1/2} \tag{4.3-1}$$

where, n is the Manning coefficient, V the depth average water velocity, R is the hydraulic radius of the cross section and J the channel bed slope.

Selection of the Manning coefficient is based on the riverbed characteristics, and a method developed by Cowan (1956) is used to determine it. The range of the Manning coefficient for the given area is given in Table 4.3-2.

Table 4.3-2: Calculation of Manning coefficient for the case study area, using Cowan (1956) method

Substrate	sand interspersed with scattered areas of gravel	Basic,n1	Earth	0.02-0.032
		Irregularity,n2	Smooth	0.000
		Cross Section,n3	Alternating	0.010-0.015
		Obstruction,n4	Negligible	0.010-0.015
		Vegetation,n5	High	0.025-0.05
		Meandering,n6	Minor	0.000
			Manning Tot:	0.065-0.112

5 SET UP-CALIBRATION OF HYDRODYNAMIC MODEL

5.1 General

Hydrodynamic simulations for the area were made with a hydrodynamic model (using the TELEMAC-2D software), solving the continuity and momentum equations that describe the 2-D flow field in the river area. The model uses the finite element method and a structured computational mesh to solve the equations 5.1-1 through 5.1-3 and calculates water depth and the U, V velocity components at each node.

Continuity equation:

$$\frac{\partial h}{\partial t}+u\nabla(h)+hdiv(u)=S_h \qquad (5.1\text{-}1)$$

Momentum equations:

$$\frac{\partial u}{\partial t}+u\nabla(u)=-g\frac{\partial Z}{\partial x}+S_x+\frac{1}{h}div(hv_t\nabla u) \qquad (5.1\text{-}2)$$

$$\frac{\partial v}{\partial t}+u\nabla(v)=-g\frac{\partial Z}{\partial y}+S_y+\frac{1}{h}div(hv_t\nabla v) \qquad (5.1\text{-}3)$$

where h is the water depth, u, v are the velocity components in the x and y direction of a 2-D Cartesian coordinate system, t the time, Z is the free surface elevation, g the acceleration of gravity, v_t is the eddy viscosity and Sx, Sy are source terms that represent the Coriolis force and the bottom friction in the x, y direction.

For the description of the turbulent flow, the standard k-ε model is used and equations 5.1.-4 through 5.1-6 are solved.

$$\frac{\partial k}{\partial t}+\vec{u}\cdot\nabla(k)=\frac{1}{h}div(h\frac{v_t}{1.0}\nabla k)+P-\varepsilon+G \qquad (5.1\text{-}4)$$

$$\frac{\partial \varepsilon}{\partial t}+\vec{u}\cdot\nabla(\varepsilon)=\frac{1}{h}div(h\frac{v_t}{1.3}\nabla \varepsilon)+\frac{\varepsilon}{k}(1.44P-1.92\varepsilon)-1.44\frac{\varepsilon}{k}G \qquad (5.1\text{-}5)$$

$$v_t=0.09\frac{k^2}{\varepsilon} \qquad (5.1\text{-}6)$$

where P is the turbulent energy production term, G is a source term for the gravitational forces, and equation 5.1-6 relates v_t to the average turbulent kinetic energy k and the rate of dissipation ε.

5.2 Defining the computational mesh

The computational mesh for the area of interest was created using the Blue Kenue software. For the creation of the mesh an independence study was performed since the quality and fineness of the mesh can influence the results of the computation. An initial coarse computational mesh was created for the simulation and then refinement of the mesh was performed to determine a computational mesh, where possible further refinement would not alter computational results.

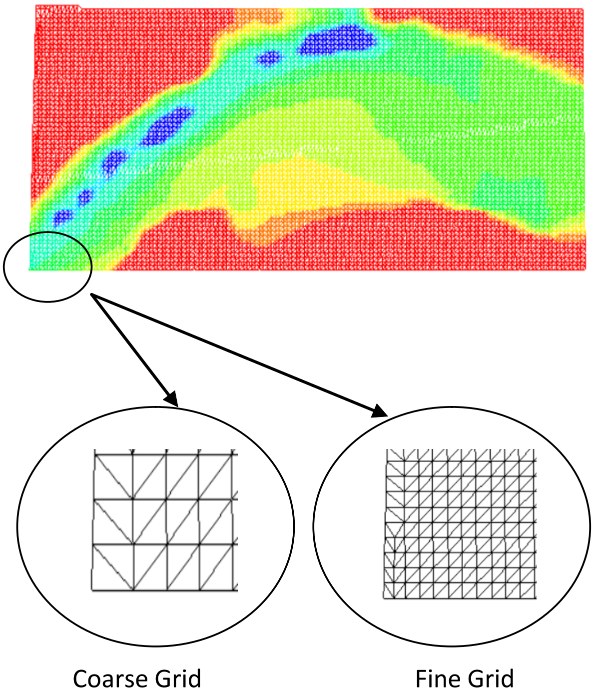


Figure 5.2-1: Refinement of the computational mesh

Table 5.2-1: Characteristics of selected computational mesh

Computational Grid	
Number of nodes	8738
Number of elements	17077
Cross channel node count	68
Along channel interval	0.5
Total area of mesh	2168.45

The computational mesh, as shown in Table 5.2-1 was created using triangular elements as seen in Figure 5.2-1, while ensuring that elements are of uniform size. Spatial coordinates for all the nodes were calculated using linear interpolation from the bathymetry data of Figure 5.2-2. Thus, the computational mesh for the river bed was created as can be seen in Figure 5.2-3.

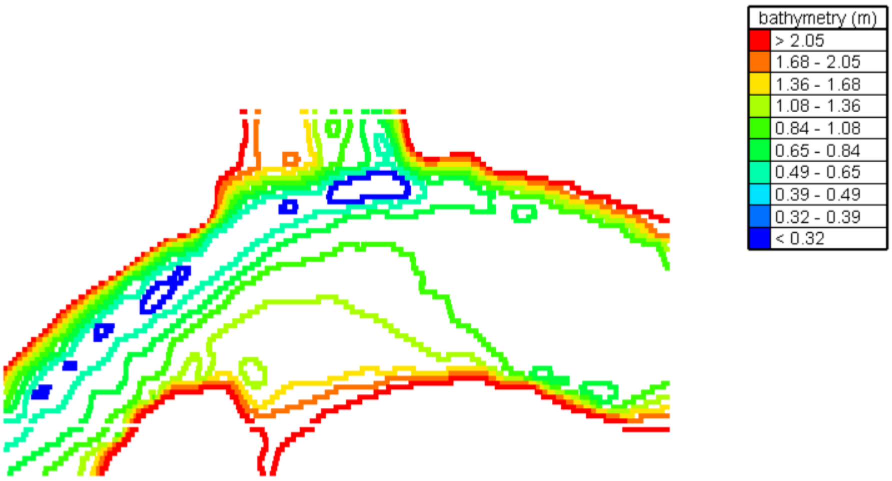


Figure 5.2-2: Bottom bathymetry

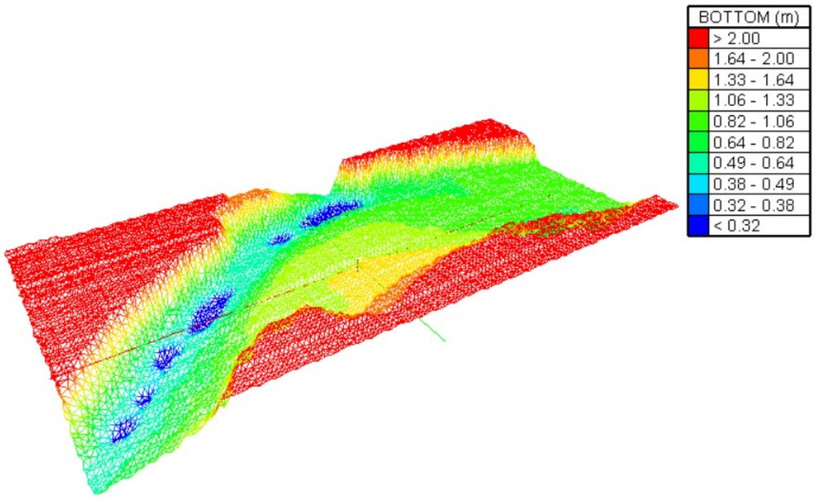


Figure 5.2-3: Computational mesh for river bed

5.3 Setup of the hydrodynamic TELEMAC-2D model

Setup of the hydrodynamic model was made using the FUDAA-PREPRO software. Three boundary conditions were set:

1. At the upstream cross section of the area we used an inflow condition, setting the flow rate equal to a specific value (Q_1),
2. at the middle part of the right side of the river, where water is diverted to the Jedsted Mill Fish Farm, an outflow condition is used by setting a constant outflow rate (Q_2), and
3. at the downstream end of our simulated area we set the water elevation equal to a specific value (H_3), denoting water surface elevation of the area, as seen in Table 4.1-3.

Next, the computational time step was considered by insuring that the Courant-Friedrich-Levy equation (4.2-1) holds true, where $C\max = 1$.

$$C = \frac{u\Delta t}{\Delta x} + \frac{v\Delta t}{\Delta y} \leq C\max \qquad (4.2\text{-}1)$$

where u, v are the velocity components in the x and y direction, Δt is the time step, Δx and Δy are the length intervals in the x and y direction and C the Courant number.

Basic simulation parameters entered can be seen in Table 5.3-1.

Table 5.3-1: Setup parameters of the TELEMAC-2D simulation

Hydrodynamic model input		
Simulation time	until steady state is reached	
Time step (s)	0.0010	
Bottom Friction	Manning	
Turbulence model	k-ε	
Initial condition	Constant Elevation (m)	1.5

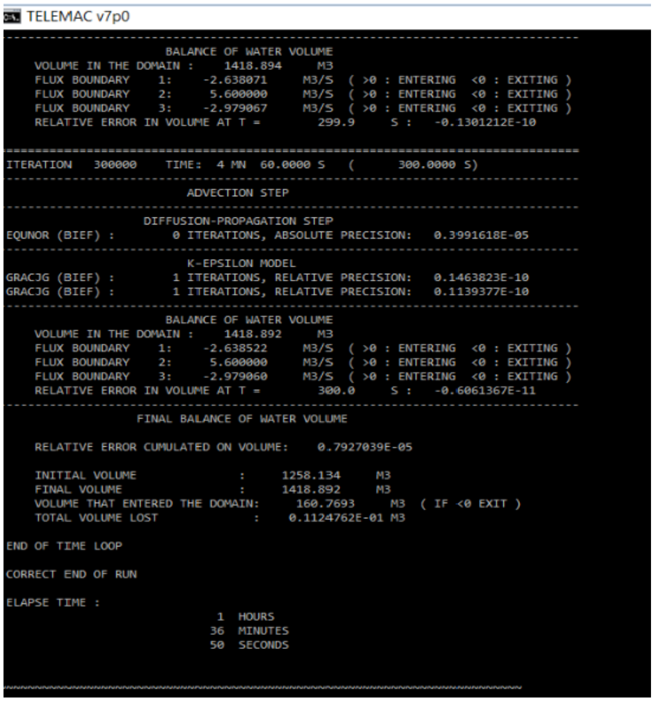
5.4 Calibration/verification of hydrodynamic model

Calibration of the model was based on the discharge calculated by the velocity and water depth contour lines of Figure 4.3-1, 4.3-2 and the cross sections (Δ1, Δ2, Δ3) of Figure 4.3-3 through 4.3-5. Boundary conditions for the calibration of the model can be seen in Table 5.4-1 and outputs of the calibration run are shown in Figure 5.4-1, and 5.4-2.

Table 5.4-1: Boundary conditions used for calibrating TELEMAC-2D

Boundary	Boundary condition	Values
Upstream boundary	Boundary with Prescribed Q (inflow)	Q=5.66 (m^3/s)
Jedsted Mill Fish Farm boundary	Boundary with Prescribed Q and H (outflow)	Q=-2.95 (m^3/s)
		H=2.0 m
Downstream boundary	Boundary with Prescribed H	H=1.8 m

The model was calibrated to determine the appropriate Manning coefficients at each segment of the simulated area by comparing measured versus simulated velocities for the boundary conditions of Table 5.4-1. The acceptable range of the Manning coefficient for the Jedsted Mill Fish Farm area can be found at Table 4.3-2.



```
TELEMAC v7p0
--------------------------------------------------------------------------------
                  BALANCE OF WATER VOLUME
    VOLUME IN THE DOMAIN :    1418.894     M3
    FLUX BOUNDARY    1:    -2.638071     M3/S  ( >0 : ENTERING  <0 : EXITING )
    FLUX BOUNDARY    2:     5.600000     M3/S  ( >0 : ENTERING  <0 : EXITING )
    FLUX BOUNDARY    3:    -2.979067     M3/S  ( >0 : ENTERING  <0 : EXITING )
    RELATIVE ERROR IN VOLUME AT T =        299.9      S :   -0.1301212E-10

================================================================================
ITERATION   300000    TIME:  4 MN  60.0000 S   (      300.0000 S)
--------------------------------------------------------------------------------
                    ADVECTION STEP
--------------------------------------------------------------------------------
                DIFFUSION-PROPAGATION STEP
EQUNOR (BIEF) :        0 ITERATIONS, ABSOLUTE PRECISION:   0.3991618E-05
--------------------------------------------------------------------------------
                    K-EPSILON MODEL
GRACJG (BIEF) :        1 ITERATIONS, RELATIVE PRECISION:   0.1463823E-10
GRACJG (BIEF) :        1 ITERATIONS, RELATIVE PRECISION:   0.1139377E-10
--------------------------------------------------------------------------------
                  BALANCE OF WATER VOLUME
    VOLUME IN THE DOMAIN :    1418.892     M3
    FLUX BOUNDARY    1:    -2.638522     M3/S  ( >0 : ENTERING  <0 : EXITING )
    FLUX BOUNDARY    2:     5.600000     M3/S  ( >0 : ENTERING  <0 : EXITING )
    FLUX BOUNDARY    3:    -2.979060     M3/S  ( >0 : ENTERING  <0 : EXITING )
    RELATIVE ERROR IN VOLUME AT T =        300.0      S :   -0.6061367E-11
--------------------------------------------------------------------------------
                FINAL BALANCE OF WATER VOLUME

    RELATIVE ERROR CUMULATED ON VOLUME:    0.7927039E-05

    INITIAL VOLUME                :     1258.134     M3
    FINAL VOLUME                  :     1418.892     M3
    VOLUME THAT ENTERED THE DOMAIN:      160.7693     M3  ( IF <0 EXIT )
    TOTAL VOLUME LOST               :    0.1124762E-01 M3

END OF TIME LOOP

CORRECT END OF RUN

ELAPSE TIME :
                            1  HOURS
                           36  MINUTES
                           50  SECONDS
```

Figure 5.4-1: End of TELEMAC-2D run for model calibration

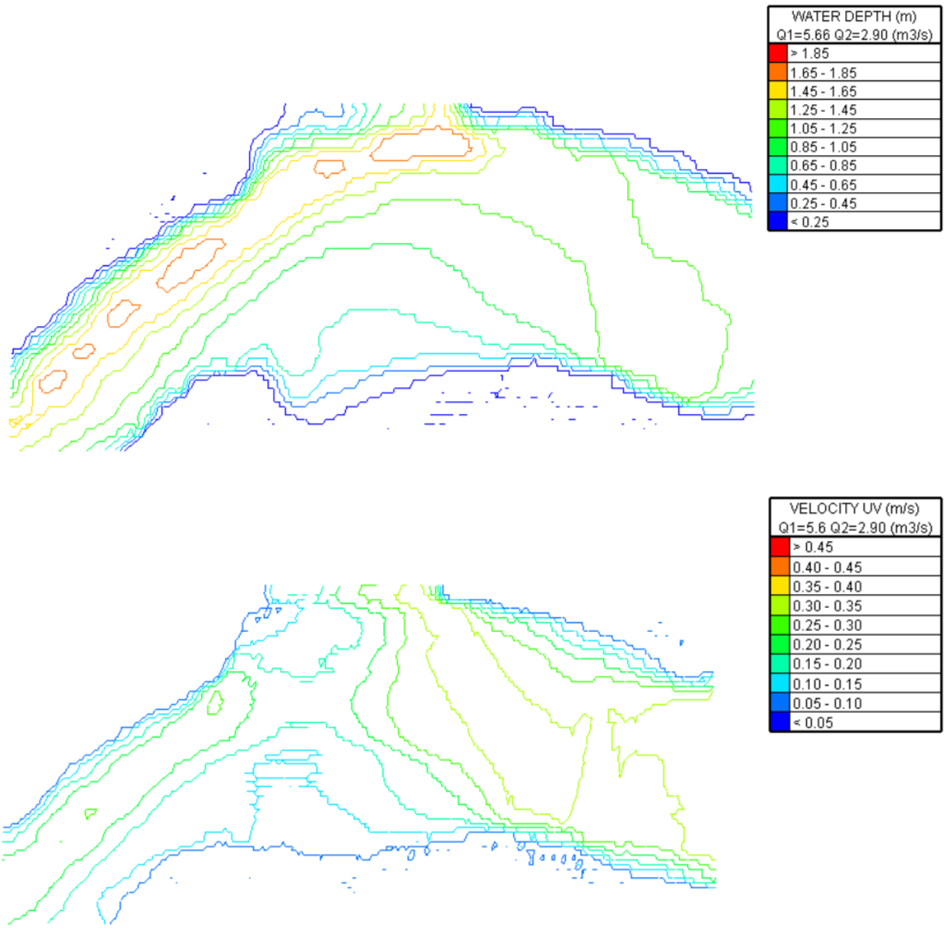


Figure 5.4-2: Water depth and depth average velocity contour lines, used for validating the hydrodynamic model. Boundary conditions are set from Table 5.4-1

6 IMPLEMENTATION OF THE MODEL FOR THE CASE STUDY

6.1 Application of the hydrodynamic model on case study

After calibrating the hydrodynamic model created with the use of TELEMAC-2D, we applied the model for the information of the case study, as seen in Table 4.1-3. Boundary conditions used as inputs for TELEMAC-2D are presented in Table 6.1-1. Flow velocities and water depth contour lines, as calculated by the hydrodynamic model can be found in Figure 6.1-1.

Table 6.1-1: Boundary conditions used for TELEMAC-2D case study simulation

Boundary	Boundary condition	Scenario
Upstream boundary	Boundary with Prescribed Q (inflow)	Q1=2.66 (m^3/s)
Jedsted Mill Fish Farm boundary	Boundary with Prescribed Q and H (outflow)	Q2=-0.53 (m^3/s)
		H2=2.0 (m)
Downstream boundary	Boundary with Prescribed H	H3=2.0 (m)

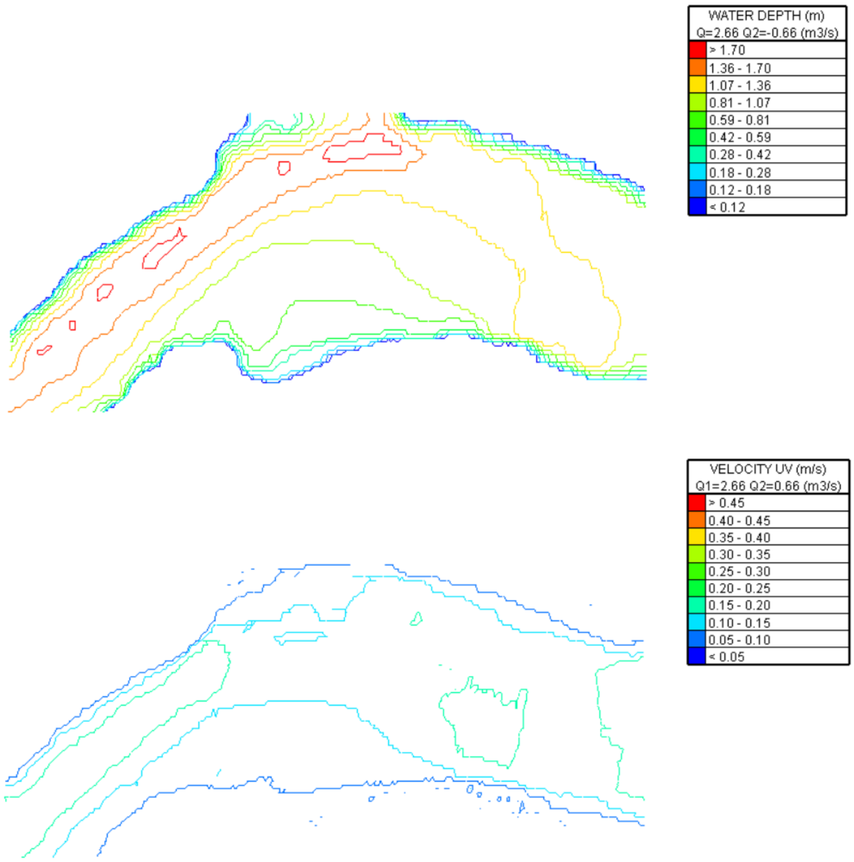


Figure 6.1-1: Contour lines for water depth and average velocity for case study discharge scenario Q1=2.66 m^3/s, Q2=-0.53 m^3/s and H3=2.0m

6.2 Application of the Fish Behavior Model – Results

The Fish Behavior Model is implemented as seen in Chapter 3.2. The computational mesh, water depths and U, V velocity components have been calculated using TELEMAC-2D. Fish paths are calculated and compared for validating purposes with fish data measurements presented in Figure 4.2-1. The location of Hp-4 (Hydrophone 4) is selected as initial fish position for the simulations.

Three cases of simulating fish paths were attempted, involving:

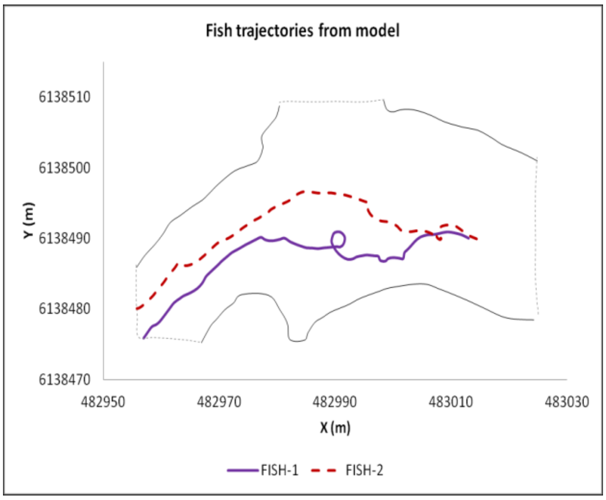
1. Fish passing through the area following the flow, using a path without sudden changes in orientation,
2. fish passing through the area following a path with a few sudden changes in orientation, and
3. fish trajectories as presented in the data measurements of Figure 4.2-1.

Using threshold values for the detection metric (DMETRIC) Thres(1)=0, Thres(2)=0.84, and Thres(3)=0.89 it was noticed that fish would follow the flow utilizing only behavior B1. Thus, passage through the area without sudden changes in orientation can be modeled using the above coefficients. Calculated fish paths are shown in Figure 6.2-1.

For simulating fish following a path with a few sudden changes in orientation, model coefficients which influence behavior decisions were adjusted and results can be seen in Figure 6.2-2.

The third case of simulating fish paths was not achieved in the present work since it was a first implementation of the proposed model.

A sensitivity analysis was performed in order to determine important coefficients of the model that influence fish trajectories and can be adjusted during model calibration to simulate fish trajectories.



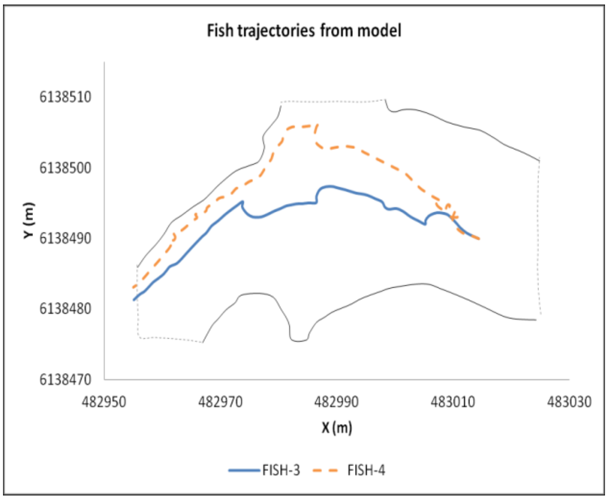


Figure 6.2-1: Simulated fish paths from Fish Behavior Model. Fish pass through the area following the flow without sudden changes in orientation (only behavior B1 is activated).

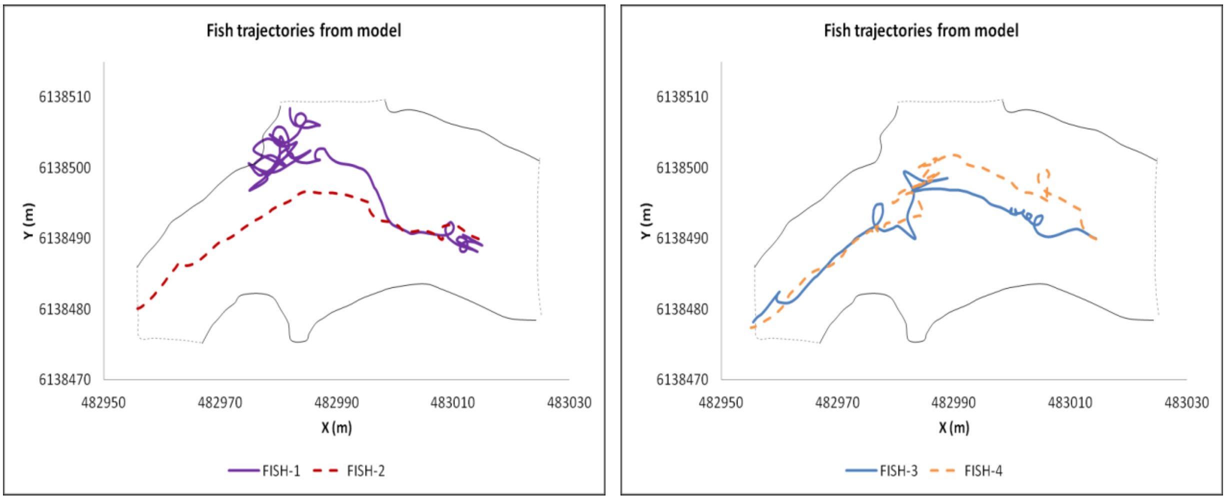


Figure 6.2-2: Simulated fish paths from Fish Behavior Model. Fish pass through the area showing sudden changes in orientation (behavior B2 and B3 are activated). FISH-1 exits the case study area into the Jedsted Mill Fish Farm

6.3 Sensitivity Analysis

Sensitivity analysis calculations have been performed for 100 fishes with the same starting location to account for stochastic values in the model. Simulation for each fish was performed separately. Initially a scenario was calculated, in order to determine the most important coefficients of the fish behavior model, which are used for the calibration of the fish behavior model.

We calculated the mean time fish spent in the area, the mean distance travelled, mean velocity and the number of fish activating behavior B1, B2 and B3 during passage. Results for the examined scenario are presented in Table 6.3-1. In total 13 coefficients were studied for their influence on fish trajectories.

As seen in Table 6.3-1, only four cases of coefficient values were found to influence results: (1) Default (see APPENDIX), (2) THRES(2) downscaled by 75%, 85% and 90%, (3) THRES(3) downscaled by 85% and 90%, and (4) minimum value for coefficient SPEEDCRU. In Figure 6.3-1 trajectories of 5 modeled fish, using the initial (default) coefficient values are shown, as well as their distance-time graph to highlight any sudden changes in velocity. In Figure 6.3-2, 6.3-3, and 6.3-4 trajectories of fish for different values of coefficients THRES(2), THRES(3) and SPEEDCRU.

Table 6.3-1: Sensitivity analysis results for 100 individual fish

Coefficient			time	distance	Mean Velocity	B1	B2	B3
Default			157.7	74.5	0.47	100	0	0
THRES(2)	-50%	0.42	157.7	74.5	0.47	100	0	0
	-75%	0.21	160.2	74.8	0.47	100	50	0
	-85%	0.13	191.7	87.5	0.46	100	95	0
	-90%	0.08	220.1	98.1	0.45	100	100	0
THRES (3)	-50%	0.45	157.7	74.5	0.47	100	0	0
	-75%	0.22	157.7	74.5	0.47	100	0	0
	-85%	0.135	153.9	75.5	0.48	100	0	11
	-90%	0.09	171.5	92.5	0.53	100	0	49
IntrUtil(1)	fixed	1	157.7	74.5	0.47	100	0	0
IntrUtil(2)	min	0	157.7	74.5	0.47	100	0	0
	max	1	157.7	74.5	0.47	100	0	0
IntrUtil(3)	min	0	157.7	74.5	0.47	100	0	0
	max	1	157.7	74.5	0.47	100	0	0
MEMACCL(2)	min	0	157.7	74.5	0.47	100	0	0
	max	1	157.7	74.5	0.47	100	0	0
MEMACCL(3)	min	0	157.7	74.5	0.47	100	0	0
	max	1	157.7	74.5	0.47	100	0	0
MEMBEH(1)	fixed	1	157.7	74.5	0.47	100	0	0
MEMBEH(2)	min	0	157.7	74.5	0.47	100	0	0
	max	0.999	157.7	74.5	0.47	100	0	0
MEMBEH(3)	min	0	157.7	74.5	0.47	100	0	0
	max	0.999	157.7	74.5	0.47	100	0	0
SPEEDBOOST	min	6	157.7	74.5	0.47	100	0	0
	max	10	157.7	74.5	0.47	100	0	0
SPEEDCRU	min	0	451.9	67.9	0.15	100	0	0
	max	2	157.7	74.5	0.47	100	0	0
SPEEDDRIF	min	0	152.2	72.2	0.48	100	0	0
	max	0.25	157.7	74.5	0.47	100	0	0

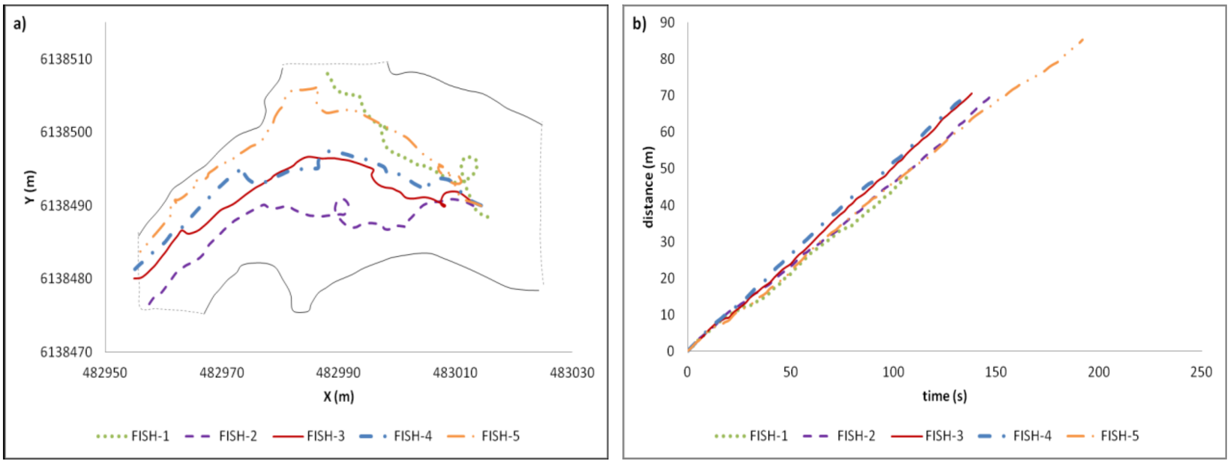
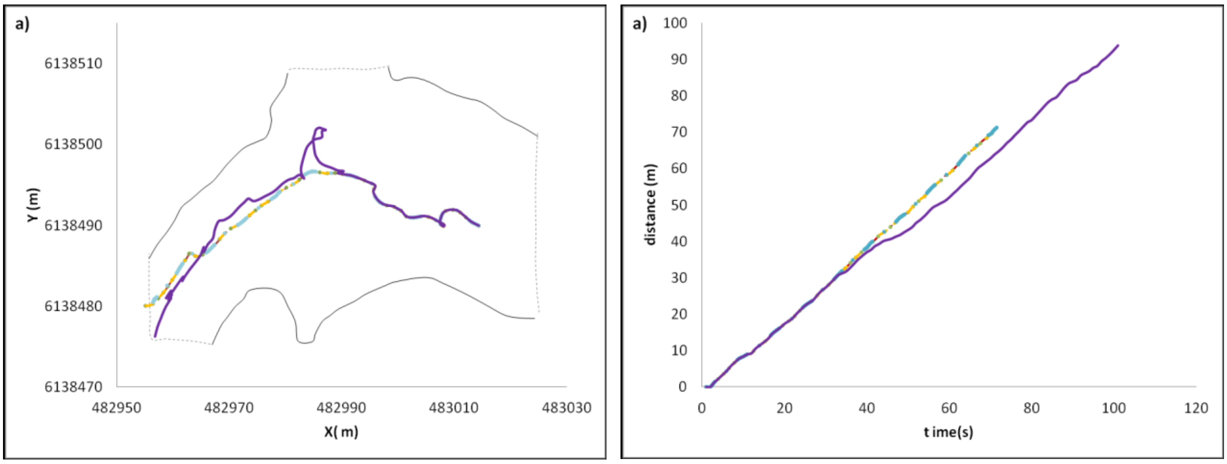
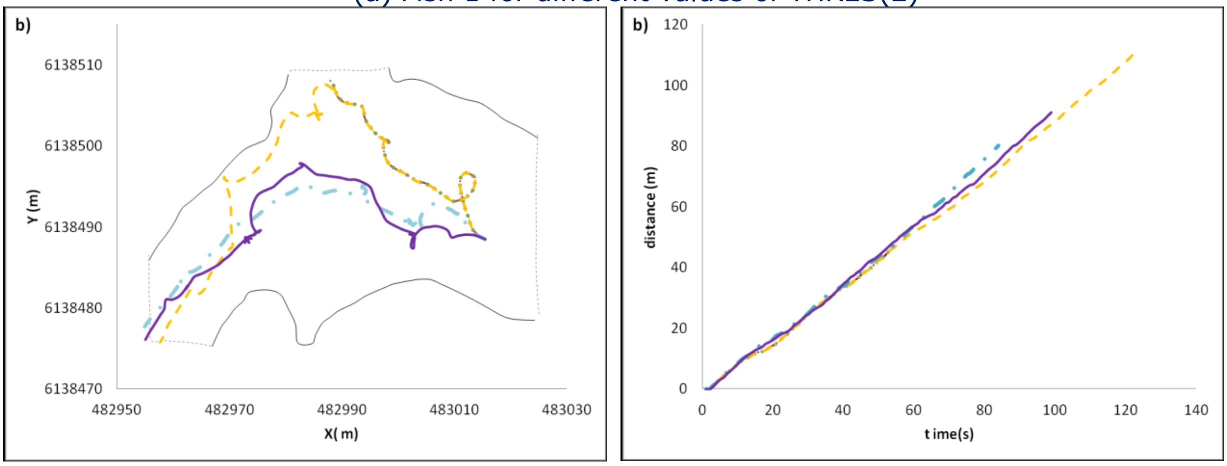


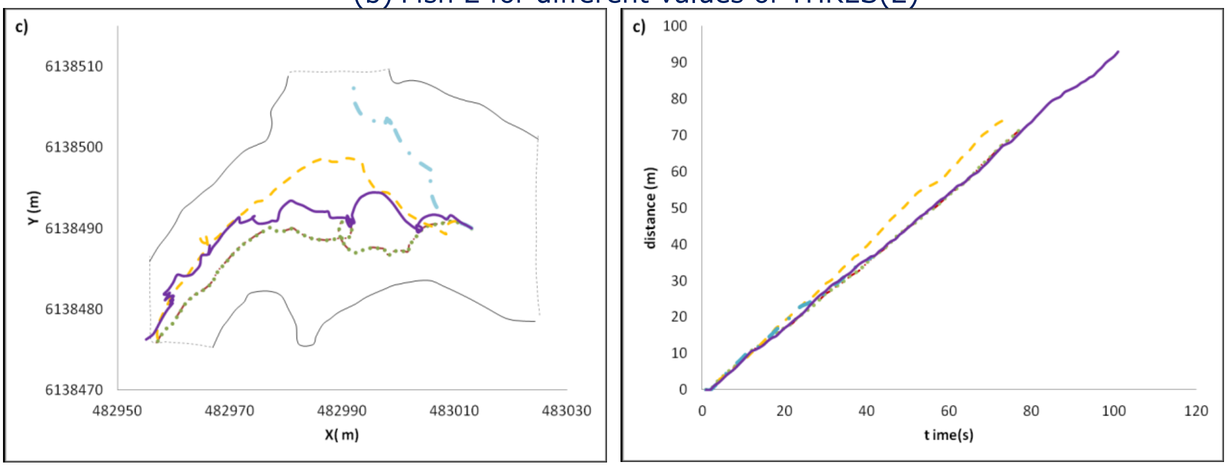
Figure 6.3-1: (a) Fish Trajectories, and (b) distance-time graph for 5 indicative fish. Default values of model coefficients are used and only B1 behavior is activated



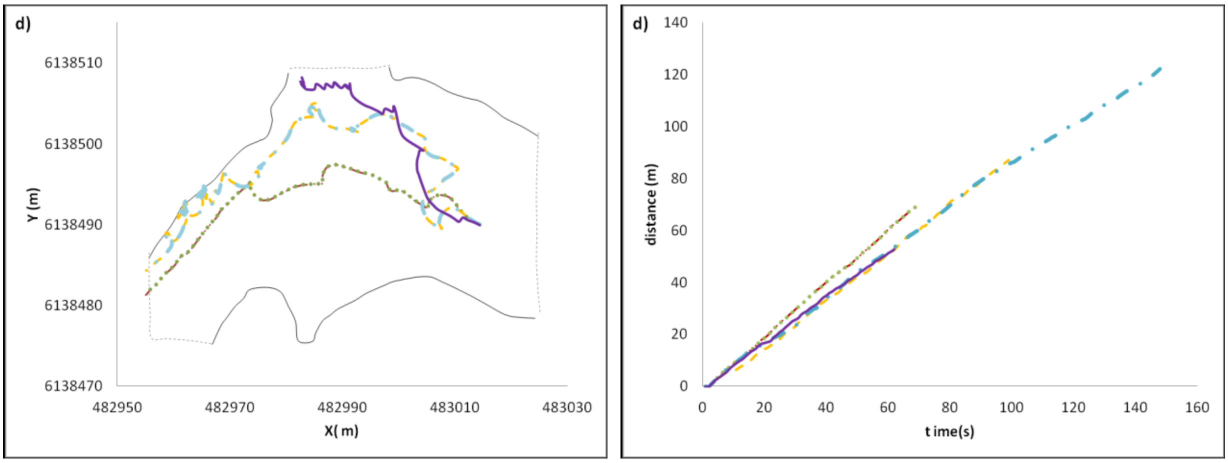
(a) Fish 1 for different values of THRES(2)



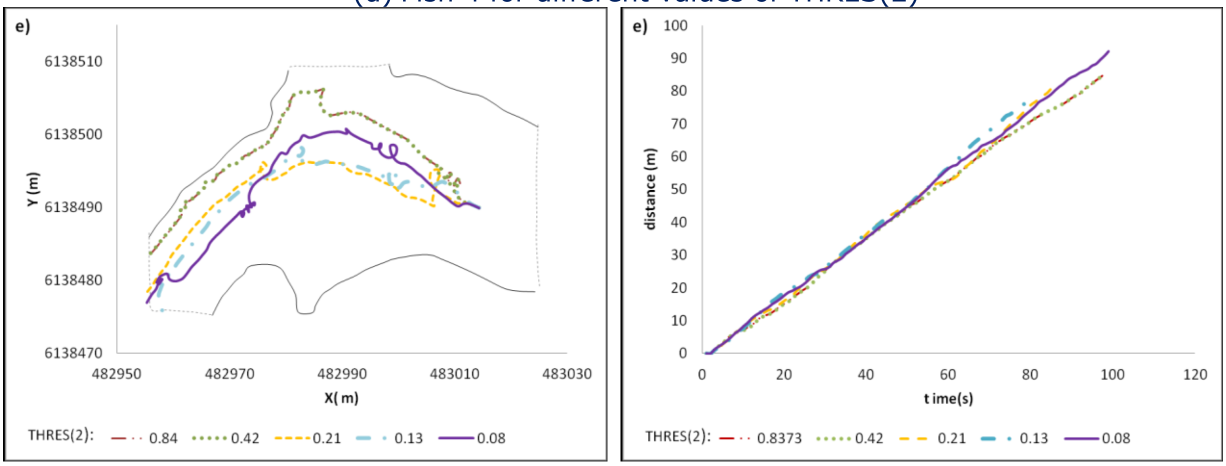
(b) Fish 2 for different values of THRES(2)



(c) Fish 3 for different values of THRES(2)

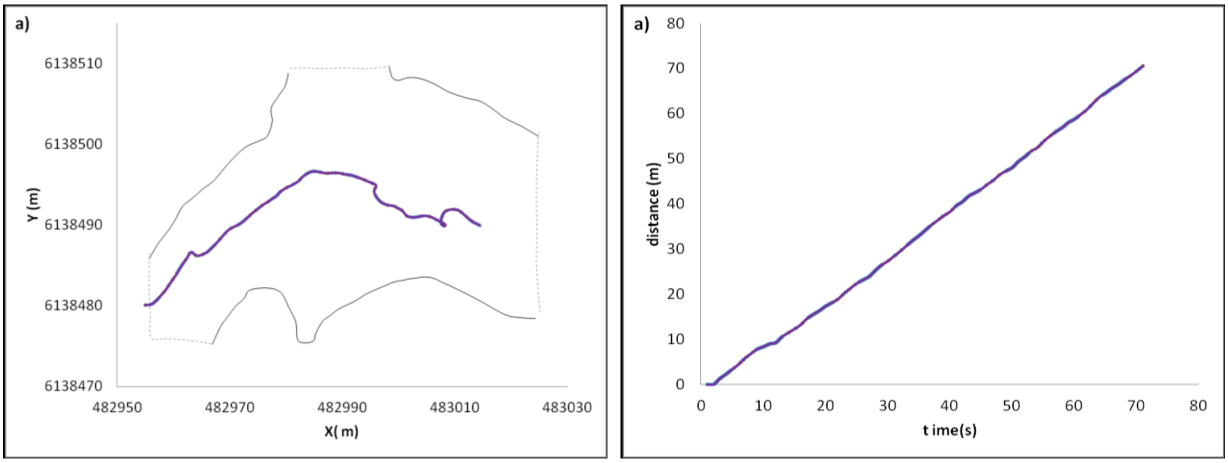


(d) Fish 4 for different values of THRES(2)

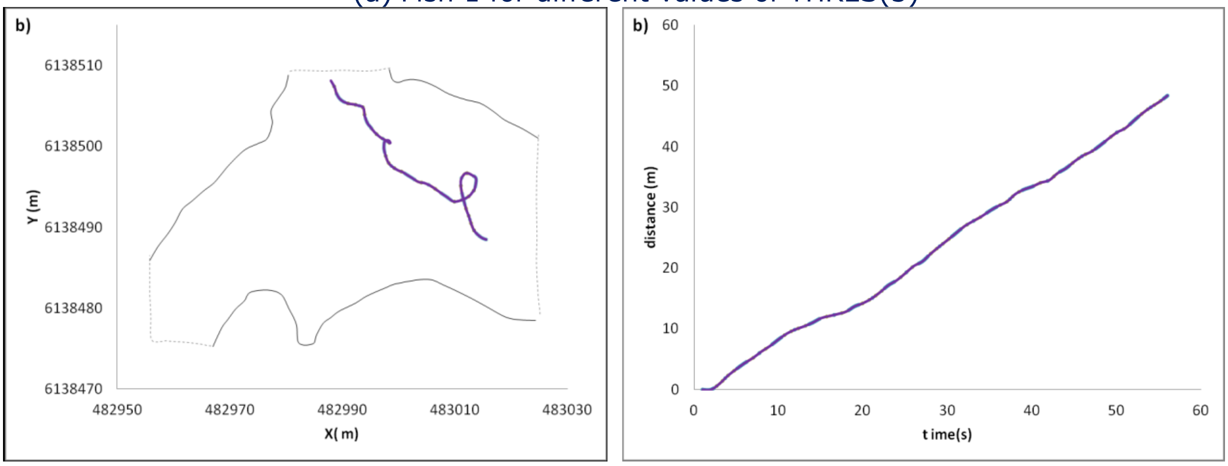


(e) Fish 5 for different values of THRES(2)

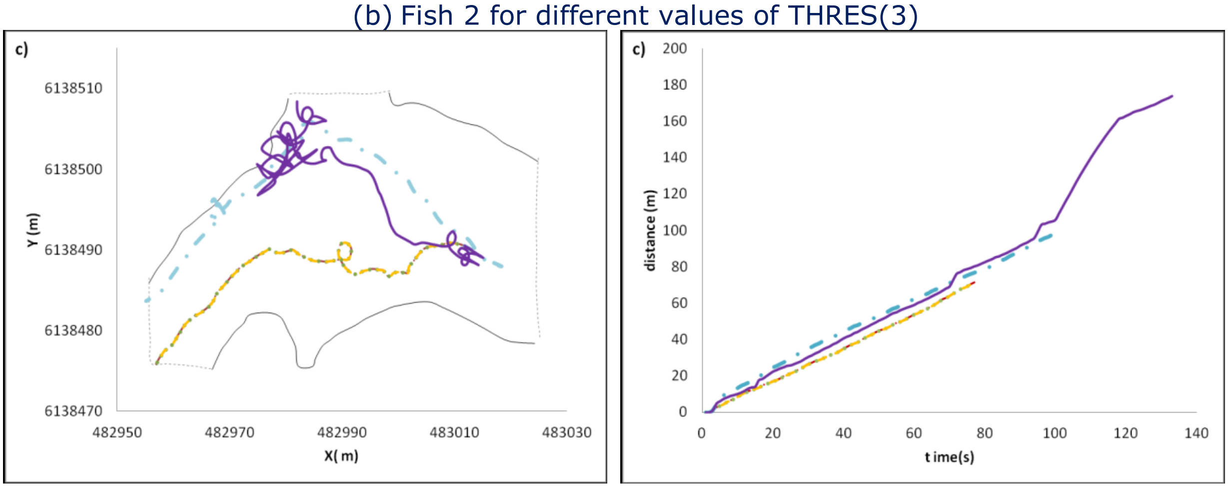
Figure 6.3-2: Indicative fish trajectories and velocity for values of coefficient THRES(2) as shown in Table 6.3-2. Fish 1-5 are represented in (a)-(e) respectively and different line types are used for every THRES(2) value



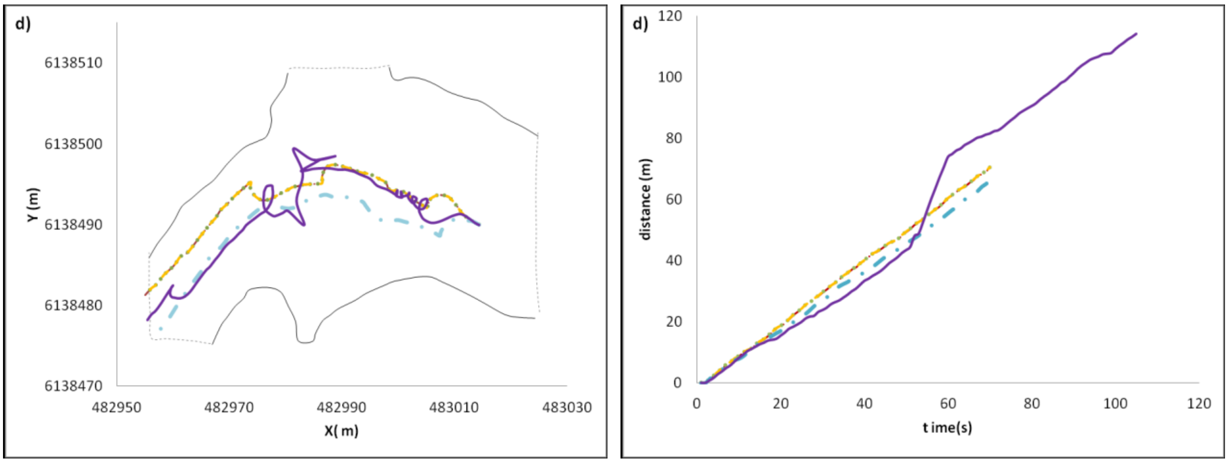
(a) Fish 1 for different values of THRES(3)



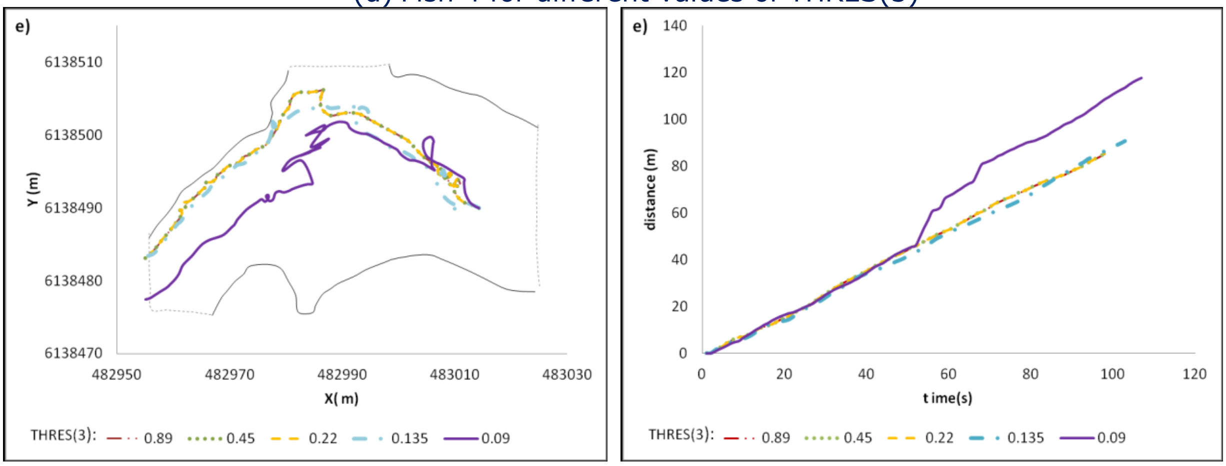
(b) Fish 2 for different values of THRES(3)



(c) Fish 3 for different values of THRES(3)

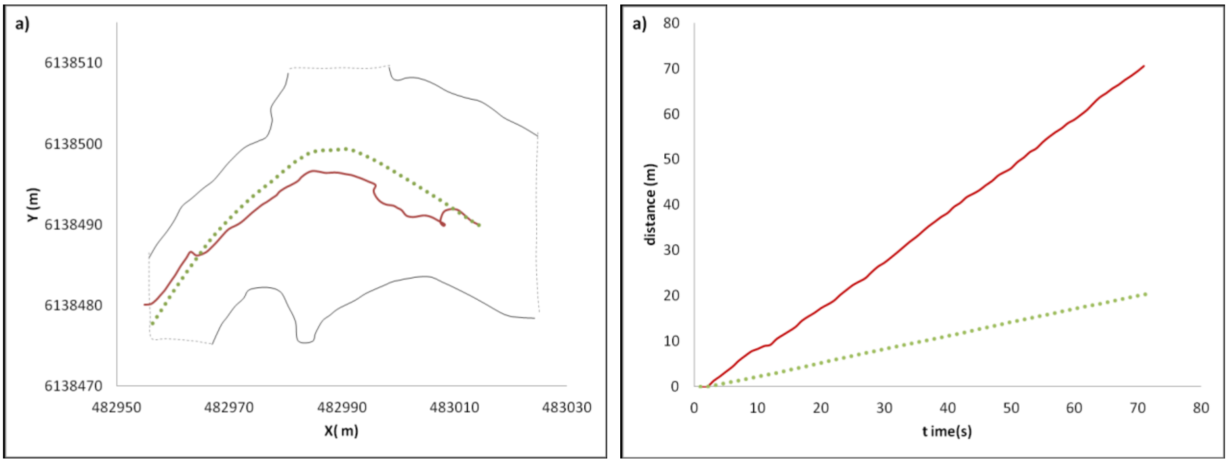


(d) Fish 4 for different values of THRES(3)

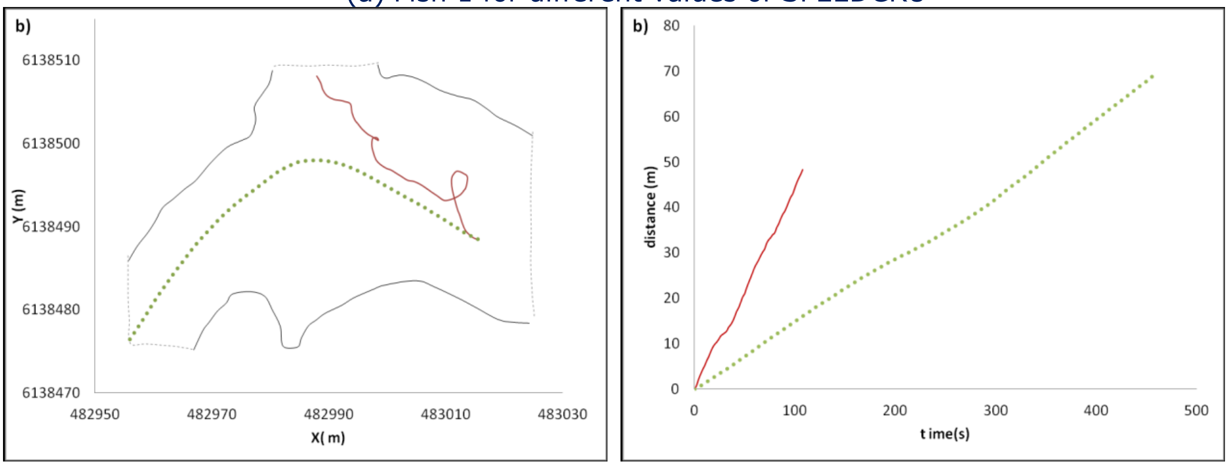


(e) Fish 5 for different values of THRES(3)

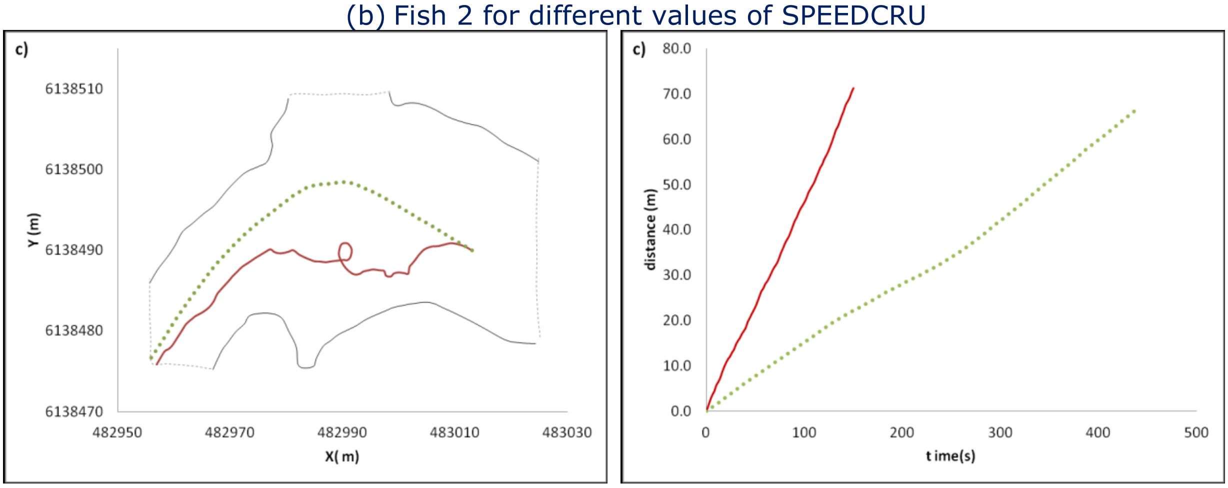
Figure 6.3-3: Indicative fish trajectories and velocity for values of coefficient THRES(3) as shown in Table 6.3-2. Fish 1-5 are represented in (a)-(e) respectively and different line types are used for every THRES(3) value



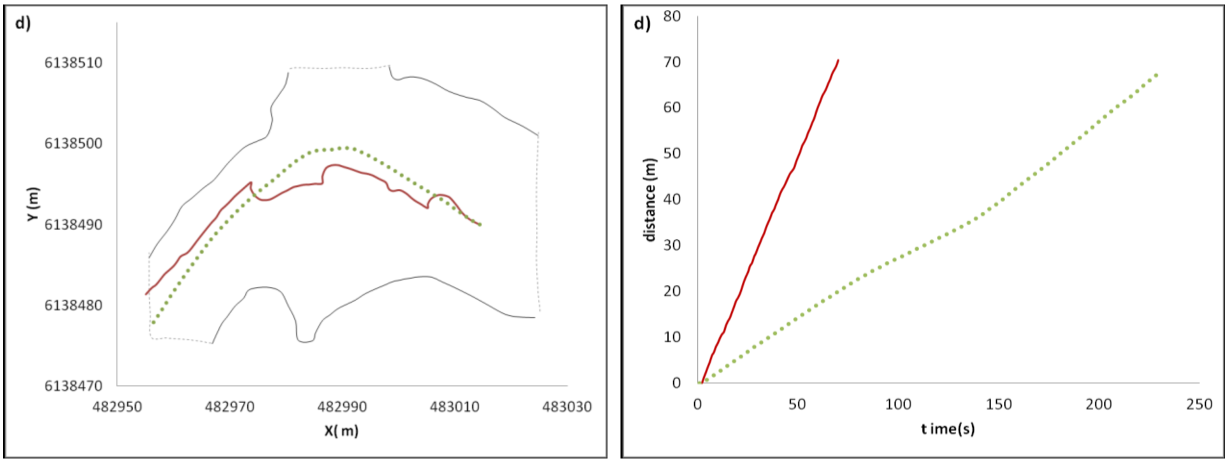
(a) Fish 1 for different values of SPEEDCRU



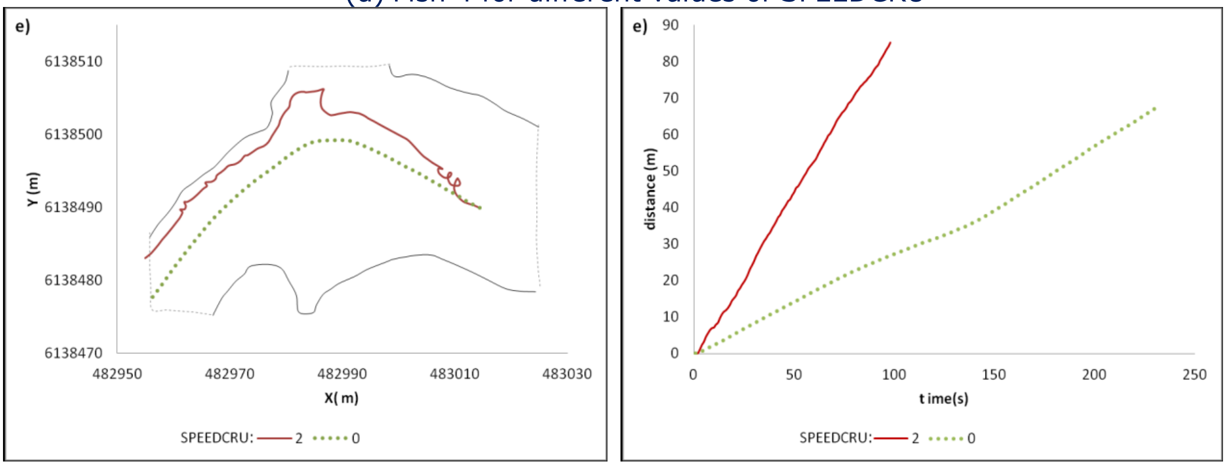
(b) Fish 2 for different values of SPEEDCRU



(c) Fish 3 for different values of SPEEDCRU



(d) Fish 4 for different values of SPEEDCRU



(e) Fish 5 for different values of SPEEDCRU

Figure 6.3-4: Indicative fish trajectories and velocity for values of coefficient SPEEDCRU as shown in Table 6.3-2. Fish 1-5 are represented in (a)-(e) respectively

As seen in Table 6.3-1 from the initial scenario, behavior B2 and B3 do not become active with coefficients within the proposed range. A 75% or greater downscale of coefficient THRES(2), managed to trigger B2 behavior responses in 50 of the 100 simulated fish. A downscale of THRES(3) by 85% and 90% managed to activate behavior B3 in 11, and 49 of the 100 simulated fish. Coefficient SPEEDCRU also showed different fish trajectories for its minimum value, as fish drifted with the bulk flow without energetic swimming (Figure 6.3-4).

In Figure 6.3-1 the trajectories and velocity of different fish can be seen for the default coefficient values. Using the default values of coefficients only B1 behavior is activated. Different trajectories for each fish are a result of the random values used for simulating changes in direction and speed. In Figure 6.3-2 trajectories and velocities for different values of THRES(2) are presented for each fish (total of 5 presented). For THRES(2)<0.21 the effects of behavior B2 can be seen as fish divert from their initial direction for greater threshold values. Velocity also changes when B2 is activated. In Figure 6.3-3 trajectories and velocities for different values of THRES(3) are presented for each fish (total of 5 presented). For THRES(3)=0.09 and especially for fish 3, 4 and 5 the effect of behavior B3 can be seen as fish abandon their downstream direction and move against the flow. A sudden increase in velocity is also seen when activating behavior B3.

It was determined that the most important coefficient for activating Behavior B1 and B2 are coefficients THRES(2) and THRES (3).

Coefficients THRES(2) and THRES(3) were applied with a downscale of 90% where behavior B2 and B3 were activated. A sensitivity analysis was performed calculating a) the number of fish displaying behavior B2 and B3 and b) the mean number of B2, B3 activations per fish. Coefficients MEMACCL (2), MEMBEH (3), SPEEDCRU and SPEEDBOOST were calculated for triggering behavior responses as presented in Table 6.3-2. We calculated, the number of fish activating behavior B1, B2 and B3 during passage and the number of activations per fish.

Table 6.3-2: Behavior B1, B2, B3 activation results for Scenario 4: a) THRES(2) and b) THRES(3) coefficients downscaled 90%

			THRES(2)=0.08 THRES(3) = 0.09					
Coefficient			**B1**	**B2**	**B3**	**B1/fish**	**B2/fish**	**B3/fish**
Default			100	99	46	92	31	8
MEMBEH(2)	min	0	100	99	46	92	31	8
	max	0.999	100	0	49	74	0	12
MEMBEH(3)	min	0	100	63	100	197	28	35
	max	0.998	100	99	46	92	31	8
SPEEDBOOST	min	6	100	100	49	94	23	20
	max	10	100	99	46	92	31	8
SPEEDCRU	min	0	100	100	51	249	49	2
	max	2	100	99	46	92	31	8

From the sensitivity analysis the following conclusions were drawn:

1. The most important coefficients of the model, used for activating behavior responses B2 and B3 are coefficients Threshold(2) and Threshold(3) respectively.

2. After determining values of coefficients THRES(2) and THRES(3) that activate each behavior, other coefficients start to take effect. Different coefficients are associated with behavior B2 and B3. Downscaling by 85% was able to activate behavior responses, but were only few for every fish. Therefore further analysis was needed into determining the appropriate value for THRES(2), THRES(3) coefficients.

3. THRES(2) and THRES(3) coefficients represent the threshold needed to be exceeded, by a detection metric, in order to reach awareness and a behavior event to happen. The detection metric is associated with the intensity of acceleration magnitude perceived by the fish, as well as the one it is acclimatized.

4. MMEMBEH(2) and MEMBEH(2) is the memory coefficient for behavior B2 and B3, integrating the amount of past information into the next decision, associated with the probability of obtaining a utility (realize their goal) from each behavior. Consequently, lower values of memory coefficient lead to more frequent activation of behavior B2 and B3.

5. SPEEDCRU and SPEEDBOOST is the coefficient determining the swimming speed of the modeled fish. Therefore lower values of swimming speed lead to greater passage time and activating more frequently behavior responses. Despite the activation of behavior response though, lower value of swimming speed coefficients lead to a more straight path, as flow velocities prevail over fish swimming speeds.

7 CONCLUSIONS AND PROPOSED RESEARCH

7.1 Conclusions

The following conclusions are drawn from the present study:

1. Fish behavior is possible to be simulated with the use of the proposed fish behavior model based on hydrodynamic stimuli as cues for activating behavior responses.

2. A single fish can perceive stimuli from spatial acceleration magnitude and then choose among the behaviors:

   i. B1, to swim along with the flow, which involves orienting itself with the flow and swimming within an angle of $\pm 20^{o}$ of the direction of the flow.

   ii. B2, to swim towards regions of faster flows, facilitating downstream migration through obstacle avoidance and limiting exposure to turbulence.

   iii. B3, to swim against flow vector, which is an escape response, where fish abandons downstream migration to swim upstream.

   Behaviors B2 and B3 are associated with changes in acceleration.

3. Presence of acceleration cues can trigger behaviors B2 and B3. Activation of these behaviors can be achieved through the calibration of the proposed model.

4. The most important coefficients of the model are coefficients Threshold(2), Threshold(3).

   i. Threshold(2) represents the minimum threshold of the fish Detection Metric, necessary to recognize the possibility of activating behavior B{2}; lower values result to more frequent activation of behavior B{2} and vice versa.

   ii. Threshold(3) represents the minimum threshold of the fish Detection Metric, necessary to recognize the possibility of activating behavior B{3}; lower values result to more frequent activation of behavior B{3} and vice versa.

5. The proposed model despite succeeding in activating basic behavior responses and simulating certain movement behaviors, fails to simulate fish movement as presented by all the given experimental data and further research is needed.

7.2 Proposed research

A first implementation of the model suggests that it is possible to simulate fish behavior in river flows. It is yet to be calibrated for every behavior presented by data measurements. In order to further expand the present work the following research is proposed:

1. An in depth study of fish data measurements, combining fish position and velocity with fish behavior documented in relative literature, in the scope of determining more precise measurements of fish velocities for each behavior response, and better understanding hydrodynamic and environmental cues influencing behavior decision.

2. Refinement and further development of the fish behavior model procedures, in order to more accurately simulate fish swimming during downstream migration, including a simulation of fish behavior and movement in three dimensional space, while incorporating other behavior responses. An intermediate behavior response is

proposed, between behavior B1 and B2, where fish changes orientation facing upstream and drifts passively with the flow, as well as a behavior response for changing swimming depth, possibly associated with pressure.

3. An application of the proposed model in other areas, containing data measurements of fish downstream migration, determining its ability to simulate fish behavior in different areas, making it appropriate for general use in river flows, by determining key factors in the model, which allow it to simulate fish behavior in different areas.

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APPENDIX

Table of parameters and variables

Variable/Parameter	Reference	Value
A0	Acceleration arbitary reference	10^{-6}
AccMg(:,:)	Acceleration Magnitude	
ACCSEN	The acceleration magnitude for node nearest sensor point	
activeB1_B2_B3.txt		
AM	Scaled Acceleration Magnitude- decibel scale	10^{-4}
angleXY	XY plane movement angle in respect of the flow	
ANGMAIN(2)	Angle in degrees of main direction for sensory point 2	0^{o}
ANGMAIN(3)	Angle in degrees of main direction for sensory point 3	180^{o}
ANGMAIN(4)	Angle in degrees of main direction for sensory point 4	90^{o}
ANGMAIN(5)	Angle in degrees of main direction for sensory point 5	-90^{o}
ANGVAR	Flexibility angle from main direction	
B2behav(sensNUM)	Inverse value of FLOWVELMg for each sensor point (fish selects minimum value in B2 Behavior)	
BESTB2beh2	2nd sensor point with max flow speed in behavior B2	
BESTB2beh3	3rd sensor point with max flow speed in behavior B2	
BESTB2beh4	4th sensor point with max flow speed in behavior B2	
BESTB2behav	Sensor point with max flow speed in behavior B2	
BESTB2Z	Sensor point with max flow speed in Z plane (vertical)	
BESTVELTOT	Sum of flow speeds of best sensory points	
BESTXYcount	Counter indicates number of sensor points with max velocity in Behavior B2	
BESTXYL	Sensor point in the left	
BESTXYR	Sensor point in the right	
BOT(:,:)	Bottom elevation for each node	
Coeff40	Add range of variables to non- cardinal sensory points location	0
Coeff42	Lower bound for first time acclimatization	0.4
COUNTB1	Counter indicates the total number of times fish adapted behavior B1	
COUNTB1tot	Counter indicates the total number of behavior B1 activation for all simulated fish	
COUNTB2	Counter indicates the total number of times fish adapted behavior B2	
COUNTB2tot	Counter indicates the total number of behavior B2 activation for all simulated fish	
COUNTB3	Counter indicates the total number of times fish adapted behavior B3	
COUNTB3tot	Counter indicates the total number of behavior B3 activation for all simulated fish	
COUNTFB1	Counter indicates the number of simulated fishes adapt	

	behavior B1	
COUNTFB2	Counter indicates the number of simulated fishes adapt behavior B2	
COUNTFB3	Counter indicates the number of simulated fishes adapt behavior B3	
DATA_BOTTOM.dat	Input from TELEMAC containing X, Y and bottom elevation for each node	
DATA_FISH_columns.txt	Input from TELEMAC containing number of nodes for each row	
DATA_FREE_SURFACE.dat	Input from TELEMAC containing X, Y and free surface elevation for each node	
DATA_VELOCITY UV.dat	Input from TELEMAC containing X, Y and velocity components U, V for each node	
DELTA	Percent of sensor point random increase	2
dist	The distance between fish or sensory point and the current mesh node	
distold	The last lower fish/sensor- node distance	
DMETRIC(:,:)	Agent Decision Metric	
DT	Time step between each movement performed by fish (s)	2
DX	Displacement in each simulated movement	
Dxtot	Total displacement	
EVENT(:,:)	Boolean event	
filenum	Counter indicates FISH_POSITION output file for each fish	
fish_BehavCoeff.txt	Input file containing thresholds and coefficients related to fish behavior	
fish_charact.dat	Input file containing swimming speeds related to fish behavior and simulated fish length	
fish_location.dat	Input file containing fish position, orientation and number of simulated fish	
FISH_POSITIONS01.txt	Output file containing fish position (XF, YF) and TIME for first fish	
FISHANGXY	Fish angle in XY direction	
FISHANGZ	Fish angle in Z direction	
FISHITER	Counter indicates the number of the simulated fish	
FISHLENG	Fish Length (m)	0.19
FISHNUM	Number of fish simulated for each project	
FISHVELnew(1)	Fish axial velocity component in direction relative to fish	
FISHVELnew(2)	Fish vertical velocity component in direction relative to fish	
FISHVELXYZ(1)	Fish U velocity copmonent in cfd- based XYZ direction	
FISHVELXYZ(2)	Fish V velocity copmonent in cfd- based XYZ direction	
FLOWANGXY	The flow vector angle in xy plane	
FLOWVEL(NSEN)	Flow speed perceived in sensory point	
fout	Counter indicates fish reaches a border node	
FvelMgtot	The mean velocity magnitude per simulated movement	
IFISH	The I- coordinate of the node nearest to fish location	

IntAccPast(:,:)	Perceived intensity of Acceleration stimulus by fish through sensory ovoid	
IntAccPres(:,:)	Value of the Acceleration intensity stimulus the fish has already acclimatized	
IntrUtil(1)	Subjective intrinsic value of behavior B1 in realizing the goal	1
IntrUtil(2)	Subjective intrinsic value of behavior B2 in realizing the goal	0.5
IntrUtil(3)	Subjective intrinsic value of behavior B3 in realizing the goal	1
ITERMAX	Maximum number of movements the fish perfom during simulation	300
IXSEN	The I- coordinate of the node nearest to sensory point location	
IYSEN	The I- coordinate of the node nearest to sensory location	
JFISH	The J- coordinate of the node nearest to fish location	
JMAX(I)	The number of nodes for each row	
MEMACCL(2)	Memory Coefficient for acclimatization in behavior B2	0.999
MEMACCL(3)	Memory Coefficient for acclimatization in behavior B3	0.95
MEMBEH(1)	Memory Coefficient for behavior B1	1
MEMBEH(2)	Memory Coefficient for behavior B2	0.
MEMBEH(3)	Memory Coefficient for behavior B3	0.998
NBEH	Idicates each of agent (fish) behavior	
NCOEFF	Coefficient to scale minimum sensory point distance	4.5
NDESIC	Indicates behavior fish adapts (>=1)	
NSEN	Sensory point number	
NUMEVENT(:,:)	Number of events for an agent	
NX	A large integer number for matrix dimensioning	400
NY	A large integer number for matrix dimensioning	200
pi	π number	3.14159
PROB(:,:)	Propability of response	
R1	Random number from uniform distribution	[0,1]
R3	Random number from uniform distribution	[0,1]
RINC	Random Increase of sensory point Distance	
RND	Range of the variability to non- cardinal locations	
RR	Random from uniform distribution	
RRB1	Random from uniform distribution angle for B1	[-1,1]
RRB2	Random from uniform distribution angle for B2	[-1,1]
RRB3	Random from uniform distribution angle for B3	[-1,1]
RRSQD	Random from seed number	
sim_info_in.dat	Input file containing time step, initial time and maximum number of movements per simulation	
SPDIST	Sensory Point Distance	
SPEEDBOOST	Burst speed for selected fish (fish lengths*sec^{-1})	10
SPEEDDRIF	Drift speed for selected fish (fish lengths*sec^{-1})	0.25

SPEEDFISH	Fish speed for the next move	
SPEEDSUST	Sustained speed for selected fish (fish lengths*sec^{-1})	6
SPEEDXY	Fish Speed in XY plane	
SPREEDCRU	Cruise speed for selected fish	2
SQDX(1)	Sensory Ovoid X for point 1 (fish itself)	
SQDX(2)	Sensory Ovoid X for point 2 (direction fish head is pointing)	
SQDX(3)	Sensory Ovoid X for point 3 (direction of the fish' s tail)	
SQDX(4)	Sensory Ovoid X for point 4 (to the left of the fish)	
SQDX(5)	Sensory Ovoid X for point 5 (to the right of the fish)	
SQDY(1)	Sensory Ovoid Y for point 1 (fish itself)	
SQDY(2)	Sensory Ovoid Y for point 2 (direction fish head is pointing)	
SQDY(3)	Sensory Ovoid Y for point 3 (direction of the fish' s tail)	
SQDY(4)	Sensory Ovoid Y for point 4 (to the left of the fish)	
SQDY(5)	Sensory Ovoid Y for point 5 (to the right of the fish)	
SUR(:,:)	The surface elevation for each node	
TEMPANGLE	An angle used for computations	
THRES(1)	Threshold value for behavior B1	0
THRES(2)	Threshold value for behavior B2	0.8373
THRES(3)	Threshold value for behavior B3	0.89
TIME	Time since behavior movement simulation started	
TOPANG	The top value for random angle variations	
U(:,:)	The U velocity component for each node	
UTIL(:,:)	Expected Utility for each behavior	
UTILMAX	The max of each behavior expected Utilities	
V(:,:)	The V velocity component for each node	
VELSEN(1,:)	The U velocity component for node nearest sensor point	
VELSEN(2,:)	The V velocity component for node nearest sensor point	
X(:,:)	The X- coordinate for each node	
XF	Fish X- coordinate in global system	
XFold	The X- coordinate for past fish location	
XSEN	Sensory point X coordinate in global system	
Y(:,:)	The Y- coordinate for each node	
YF	Fish Y- coordinate in global system	
YFold	The Y- coordinate for past fish location	
YSEN	Sensory point Y coordinate in global system	