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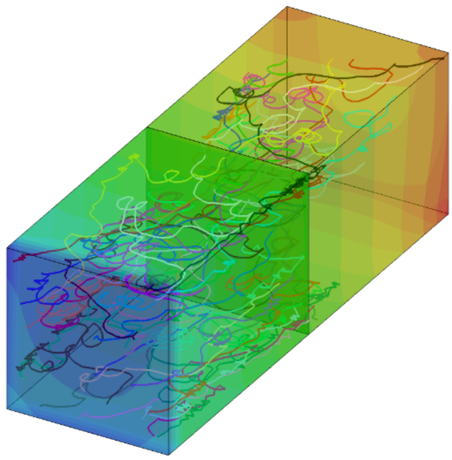

Mathematical modeling of fish-behavior in water bodies

Savvas Giannoulis – Nikolatos

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Supervisor: A. I. Stamou, Professor NTUA

Abstract

In the present work, a background research review on available fish behavior models in the literature was conducted to identify a mathematical model that is able to model fish behavior in Fish Passes; based on this review, it was found that ELAM is probably the most appropriate model. This model was decoded, analyzed, and evaluated regarding its suitability for Fish-Passes by performing a series of calculations and a sensitivity analysis. The evaluation of the model included a series of calculations in a simplified rectangular calculation domain of a water body. Initially, the model was applied to determine fish trajectory and verify qualitatively fish's ability to react to a large variety of stimuli that is exposed to; it was verified that the fish can choose among 4 possible behaviors: B{1}, to swim along with the flow; this consists of a Biased Correlated Random Walk in the direction of the flow, B{2}, to swim towards regions of faster flows thus achieving reduction of force exchange, facilitating downstream migration through obstacle avoidance and limiting exposure to turbulence, B{3}, to swim against flow vector, which is an escape response, where fish abandons downstream migration to swim upstream, and B{4}, to swim vertically toward acclimatized depth; this orients swimming to acclimatized depth if not already accomplished by other behaviors. Behaviors B{2} and B{3} are associated with changes in acceleration, while behavior B{4} with changes in pressure. Then, the model was applied to investigate the effect of flow characteristics, i.e. flow velocity and acceleration, and seed. Calculations depicted that it is solely the acceleration that triggers behaviors B{2} and B{3}, while significant values of acceleration magnitude are essential to activate those behaviors; however, more important is the role of acceleration gradient in perception of changes. Flow velocity provides no stimuli to the fish, but it can influence its trajectory; high velocities mitigate trajectory fluctuations and facilitate downstream migration. Finally, the seed number may have an important effect on fish trajectory; thus, it is advisable to perform the same calculations for various seed numbers. Sensitivity analysis calculations revealed that the most important coefficients of the model are: the utility of behavior B{1}, the memory coefficient for behavior B{3} and the subjective intrinsic value of behavior B{4}.

Keywords: Fish behavior modelling, Fish Passes, ecological modelling, river continuity

Περίληψη

Στα πλαίσια της παρούσας εργασίας πραγματοποιήθηκε μια βιβλιογραφική διερεύνηση για τα διαθέσιμα μαθηματικά μοντέλα συμπεριφοράς ιχθύων με στόχο να αναγνωριστεί το καταλληλότερο για διόδους ιχθύων. Με βάση αυτή τη διερεύνηση διαπιστώθηκε ότι το ELAM είναι, κατά πάσα πιθανότητα, το πιο κατάλληλο. Το μοντέλο αυτό αποκωδικοποιήθηκε, αναλύθηκε και αξιολογήθηκε αναφορικά με την καταλληλόλητα του για εφαρμογή σε διοδούς ιχθύων, με την πραγματοποίηση μιας σειράς υπολογισμών και μίας ανάλυσης ευαισθησίας. Η αξιολόγηση του μοντέλου περιελάβανε υπολογισμούς σε μια απλοποιημένη ορθογωνική γεωμετρία υπολογισμού ενός τμήματος υδάτινου σώματος. Αρχικά το μοντέλο εφαρμόστηκε για προσδιορίσει την τροχιά ενός ψαριού και για να επιβεβαιώσει ποιοτικά την ικανότητα του να αντιδρά σε μία ευρεία γκάμα ερεθισμάτων στην οποία εκτίθεται. Επιβεβαιώθηκε ότι το ψάρι μπορεί να επιλέξει μεταξύ τεσσάρων πιθανών συμπεριφορών: B{1}, κολύμβηση προς την κατεύθυνση της ροής. Αποτελείται από την κολύμβηση στην κατεύθυνση της ροής σε συνδυασμό με έναν παράγοντα τυχαιότητας (Biased Correlated Random Walk, BCRW), B{2}, κολύμβηση προς τις υψηλότερες ταχύτητες ροής, εξασφαλίζοντας μείωση των εναλλαγών στις δυνάμεις που το ασκούνται, διευκόλυνση της κατάντη μετανάστευσης μέσω της αποφυγής εμποδίων και τον περιορισμό έκθεσης σε τύρβη, B{3}, κολύμβηση αντίθετα στην κατεύθυνση της ροής, όπου συνιστά μια αντίδραση διαφυγής κατά την οποία το ψάρι εγκαταλείπει προσωρινά την κατάντη μετανάστευση και στρέφεται προς τα ανάντη, και B{4}, κολύμβηση προς το βάθος που έχει εγκλιματιστεί. Κατευθύνει το ψάρι προς το βάθος στο οποίο έχει προγενέστερα εγκλιματιστεί, εάν δεν έχει ήδη επιτευχθεί από τις άλλες συμπεριφορές. Οι συμπεριφορές B{2} και B{3} σχετίζονται με αλλαγές στις επιταχύνσεις, ενώ η συμπεριφορά B{4} με αλλαγές στην πίεση. Το μοντέλο εφαρμόστηκε για την διερεύνηση της επίδρασης των υδραυλικών χαρακτηριστικών, όπως οι ταχύτητες ροής και οι επιταχύνσεις, και του τυχαίου αριθμού που συμμετέχει στους υπολογισμούς. Από τους υπολογισμούς διαπιστώθηκε πως μόνο οι επιταχύνσεις είναι ικανές να ενεργοποιήσουν τις συμπεριφορές B{2} και B{3}, ενώ σημαντικές τιμές επιτάχυνσης είναι απαραίτητες για να ενεργοποιήσουν αυτές τις συμπεριφορές. Όμως περισσότερο σημαντικός είναι ο ρόλος των κλίσεων επιτάχυνσης στην αντίληψη αυτών των ερεθισμάτων. Η ταχύτητα ροής δεν προκαλεί ερεθίσματα στο ψάρι, αλλά μπορεί να επηρεάσει την πορεία του. Υψηλές τιμές ταχυτήτων περιορίζουν τις διακυμάνσεις στις τροχιές των ψαριών και διευκολύνουν την κατάντη μετανάστευση. Τέλος ο τυχαίος αριθμός που συμμετέχει στους υπολογισμούς μπορεί να έχει μια σημαντική επίδραση στην τροχιά του ψαριού, κατά συνέπεια συνιστάται να πραγματοποιούνται οι ίδιοι υπολογισμοί για διάφορους τυχαίους αριθμούς. Η ανάλυση ευαισθησίας έδειξε ότι οι πιο σημαντικοί συντελεστές είναι: η χρησιμότητα της συμπεριφοράς B{1}, ο συντελεστής μνήμης για την συμπεριφορά B{3} και η εσωτερική αξία χρησιμότητας της συμπεριφοράς B{4}.

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It is acknowledged that within IKYDA 2016, the Greek team has visited Germany twice, including my visit to Oskar von Miller – Institute, Obernach, where state-of-the-art experiments are conducted regarding fish passaging (see Appendix).

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A. EXECUTIVE SUMMARY

Scope of the present work

In the present work, a background research review on existing, available fish behavior models in the literature was conducted to identify a fish behavior model that is appropriate in Fish Passes.

Parts and methodology of the present work

Methodology

The present work consists of a) a background research review along with a critical discussion on the models and selection of the most suitable, b) description of the selected model in order to highlight its features and calculation procedures, c) an application to illustrate the calculations of single fish trajectory, d) presentation of flow data and seed number effect on the model calculation, e) a sensitivity analysis for critical components of the model, performed for 100 fishes and f) discussion of the results and proposition for future research.

Background research

The preliminary work consists of a background research of fish behavior models in the contemporary literature. The most sophisticated models found are presented in this study (see 2), specifically the model of Goodwin et al (2014), the model of Abdelaziz (2013), the model of Goodwin et al (2006) and the model of Haefner and Bowen (2002).

After analyzed the contemporary models we selected the most suitable one to facilitate the purposes of this study. The model of Haefner and Bowen relates forces exerted to the fish with its swimming behavior via physical characteristics of fish (length and mass), but does not includes the fish's perception regarding the environmental stimuli. Continuously, the model of Abdelaziz coupled hydraulic data with the concept of minimum energy expenditure, a discrete random-walk method and other special fish behaviors, however simulated fishes do not have time-varying attributes (other than location) which affect their simulated behavioral responses. Additionally, the model is bounded in roughened channels and pool-type channels.

Conclusively, the model of Goodwin et al is selected as the most appropriate for this study, since it takes into account fish perception of environmental stimuli and composes their movement as a response to those cues, along with a biased correlated random-walk. Moreover, the latter model has the ability to capture fish attributes observed in real fishes, such as that a fish may reject a route several times before entering, and some fish never return to a route after the first encounter.

Table A - 1: Comparison between the models

	Haefner and Bowen	Abdelaziz	Goodwin et al
Applications	Fish collection or diversion facilities	No	Bypass structures by U.S. Army Corps of Engineers and public utility districts in USA
Hydrodynamic modelling	No – Input from CFD	No – Input from CFD	No – Input from CFD

	Haefner and Bowen	**Abdelaziz**	**Goodwin et al**
Individual-Based-Model	Yes	Yes	Yes
Main output	Passage results of the facilities	Fish trajectory	Fish trajectory and Passage results
Dimensions	2D	3D	3D
Swimming behaviors	3	2	4
Choice of swimming behavior	Set of simple decision rules	Different fish passage types, for roughened and pool-type channels	Expected utility theory
Upstream migration	No	Yes	Yes
Downstream migration	Yes	Yes	Yes
Video image processing	No	Yes	No
Forces exerted to the fish	Yes	No	No
Obstacle avoidance	Yes	No	Yes
Turbulence avoidance	No	Yes	Yes
Energy expenditure	Yes	Yes	No
Random-walk method	No	Yes	Yes
Time-varying attributes	No	No	Yes
Perception of environmental stimuli	No	No	Yes
Acclimatization	No	No	Yes
Verification through observed data	Yes	Yes	Yes
Citations[1]	28	2	112
Available source code	No	No	Yes[2]

[1] source: Google Scholar
[2] After communication with Dr. Goodwin

Presentation of the ELAM model

In order to get familiar with this complex model, every part comprising it was analyzed and a scribble flow chart conducted (see 3.2).

The model receives as input a) geometry data, b) flow data for the calculation domain (flow velocities U, V, and W, and flow accelerations), c) Agents Behavior Coefficients and d) fish release location.
At the outset, the model identifies the fish release location on the respective cell, and interpolates the hydraulic data into the three-dimensional grid through a 3-D biquadratic interpolation.

◇ Creation of Sensory Points

To shape the sensory ovoid of the fish, 6 sensory rays surrounding the fish are used (the centroid of the fish is represented by the first ovoid position, so the rest are counted from 2-7). Sensory points are placed in space regarding the fish as follows:

1. The fish itself,
2. (+ X) in the direction the head of the fish is pointing,
3. (- X) in the direction of the fish's tail,
4. (+ Y) to the left of the fish,
5. (- Y) to the right of the fish,

6. (+ Z) in the direction above the fish (parallel to gravity),
7. (- Z) in the direction below the fish (direction of gravity).

All sensory points (2-7), are defined as the displacement from the location of the fish (1), 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 (RAND) - illustrated below.

$$\boldsymbol{SPDIST} = \frac{\eta}{Log_{10}\left(\frac{A_M}{A_0}\right)} \quad \text{(A - 1)}$$

$$\boldsymbol{RINC} = 1 + \boldsymbol{RRR} * \delta \quad \text{(A - 2)}$$

$$\boldsymbol{RAND} = (2 * \boldsymbol{RRR} - 1) * \ C_{40} \quad \text{(A - 3)}$$

where RRR is a random number created by the RandomFromSeed subroutine and C_{40} is the adding range of variability to non-cardinal sensory point locations (extracted from agent coefficient file). The following Table A - 2 depicts the calculations of the respective locations of sensory points.

Table A - 2: Sensory points as displacement distances from fish's location

Sensory point #2	
Sensory Ovoid X	= SPDIST * RINC
Sensory Ovoid Y	= SPDIST * RAND
Sensory Ovoid Z	= SPDIST * RAND
Sensory point #3	
Sensory Ovoid X	= -SPDIST * RINC
Sensory Ovoid Y	= SPDIST * RAND
Sensory Ovoid Z	= SPDIST * RAND
Sensory point #4	
Sensory Ovoid X	= SPDIST * RAND
Sensory Ovoid Y	= SPDIST * RINC
Sensory Ovoid Z	= SPDIST * RAND
Sensory point #5	
Sensory Ovoid X	= SPDIST * RAND
Sensory Ovoid Y	= -SPDIST * RINC
Sensory Ovoid Z	= SPDIST * RAND
Sensory point #6	
Sensory Ovoid X	= SPDIST * RAND
Sensory Ovoid Y	= SPDIST * RAND
Sensory Ovoid Z	= SPDIST * C_{41} * RINC
Sensory point #7	
Sensory Ovoid X	= SPDIST * RAND
Sensory Ovoid Y	= SPDIST * RAND
Sensory Ovoid Z	= -SPDIST * C_{41} * RINC

Where C_{41} is the fraction of xy-plane sensory point distance (from fish centroid) to use in vertical direction (SPs 6 & 7).

◇ 4 Behaviors

The calculation of fish trajectory and swimming speed is composed by a combination of 4 unique swimming behaviors available:

1. A Biased Correlated Random Walk (BCRW) in the direction of downstream flow, behavior B{1}.
2. Swimming in the direction leading to faster water, irrespective of the flow direction, behavior B{2}.
3. Temporal abandonment of downstream migration and upstream swimming orientation, behavior B{3}.
4. Swim towards acclimatized depth, behavior B{4}.

The behaviors B{1,2,3} are mutually exclusive, while behavior B{4} can coexists with any of the others.

◇ Perception of stimulus

To simulate fish swim behavior (speed and orientation), the behavioral model combined with a CFD model, as consequence of water acceleration and pressure (depth).

Weber's *"just noticeable difference"* is used to allow changes in perception of the same stimulus (water acceleration) through experience.

$$E_1(t) = \frac{I_1(t) - I_{\alpha_1}(t)}{I_{\alpha_1}(t)} \quad \text{(A - 4)}$$

$$I_1(t) = \log_{10}\left(\frac{A_M}{A_0}\right) \quad \text{(A - 5)}$$

$$I_{\alpha_1}(t) = \left(1 - m_{a_1}\right) * I_1(t) + m_{a_1} * I_{\alpha_1}(t-1) \quad \text{(A - 6)}$$

where, $I_1(t)$ is perceived intensity of Acceleration stimulus at the individual's position at time t, A_0 is an arbitrary reference equal to 10^{-6}, $I_{\alpha 1}(t)$ is perceived intensity of Acceleration stimulus to which the individual is acclimatized, m_{a1} is a coefficient within [0,1] scaling how quickly the individual acclimatizes to new intensities of the stimulus, A_M is water acceleration magnitude ($A_M \geq 2*10^{-6}$). Thus, a greater change in perceived intensity of water acceleration is necessary at a greater level of acclimatization to elicit the same response.

If $E_1(t)$ exceeds a threshold value $k_{B\{2\}} = 0.8373$ the behavior B{2} is activated, orienting the fish in the direction leading to faster water. Otherwise, if $E_1(t)$ exceeds a threshold value $k_{B\{3\}} = 0.89$ the behavior B{3} is activated; fish temporally abandons downstream migration and orients upstream.

Fish acclimatize to new pressure over time; if difference between acclimatized depth and fish elevation, $E_2(t)$, exceeds a threshold value, B{4} is triggered orienting fish to acclimatized depth.

$$E_2(t) = \left|I_2(t) - I_{\alpha_2}(t)\right| \quad \text{(A - 7)}$$

where, $I_2(t)$ is perceived intensity of Pressure stimulus at the individual's position at time t (i.e. the depth), $I_{\alpha 2}(t)$ is perceived intensity of Pressure stimulus to which the individual is acclimatized, also derived from (A-6).

If $E_2(t)$ exceeds a threshold value $k_{B\{4\}} = 1.1315$ the behavior B{4} is activated, orienting fish towards acclimatized depth.

If the fish swims upwards, m_{a2} coefficient modifies, as:

$$m_{a_2} = m_{a_2} * C_{38} \quad \text{(A - 8)}$$

where C_{38} is a memory coefficient for acclimatization fraction when fish swims upward, with a probable range: 0.9 ~ 1.0.

◇ Probability and Utility

The probability and the utility associated with each agent is calculated, where the agent with the maximum utility value is selected as the one that the fish will respond to. Perceived changes in water acceleration, $E_1(t)$, and swim bladder pressure (depth), E_2 (t), that exceed thresholds $k_{B\{2,3\}}$, and $k_{B\{4\}}$, respectively, support the weight of evidence for the related behaviors B{2,3,4}. The rise and fall in utility occur through Boolean events where $e_B(t)=1$ if perceived change exceeds k_B in a time increment and $e_B(t)=0$ otherwise. Probability, $P_B(t)$, of responding with B{j}, j=2,3,4 increases as:

$$\boldsymbol{P_B(t) = (1 - m_B)e_B(t) + m_B P_B(t-1)} \quad \text{(A - 9)}$$

where memory coefficient m_B integrates the amount of past information into the next decision following the notion that intensity or duration of activity in sensory neurons needs to pass a threshold to reach awareness.

The behavior decision is based on an objective function, utility, where each decision in the set of alternatives B{1,2,3,4} has an associated expected utility, U_B (t):

$$\boldsymbol{U_B(t) = P_B(t)u_B - C_B(t)} \quad \text{(A - 10)}$$

where u_B is the subjective intrinsic value of behavior B{j} in realizing the goal, i.e., reduction of perceived change in stimulus i=1,2, $E_i(t)$, to back within the threshold tolerance. For simplicity, cost incurred whether or not the goal is realized is set as $C_{B\{1,2,3,4\}} = 0$. Utility of B{1} is fixed over time as $U_{B\{1\}}=0.25$, but utilities of B{2,3,4} fluctuate as the fish transits the flow field. In an increment of time, the behavior B{1,2,3} with highest utility $U_B(t)$ is active. Separately encoded vertical movement B{4} is implemented when $U_{B\{4\}} \geq \beta u_{B\{4\}}$ where β=0.9.

This framework generates behaviors that, on average, maximize utility but, at any given time, may appear to be random.

◇ Behavior B{1}

The default state B{1} (swim with flow vector) is a correlated random walk biased (BCRW) in the direction of downstream water flow. Initial θ_0 coincides with the flow vector and subsequent B{1} moves occur at a persistent Δθ – with uniform variability within arc $\alpha_{B\{1,2\}}=\pm 20^{o}$ (xy-plane) and $0.5\alpha_{B\{1,2\}}$ (vertical) – until:

$$\boldsymbol{R_{[0,1]} \leq e^{(l * C_{\Delta\theta})} - 1} \quad \text{(A - 11)}$$

where, $R_{[0,1]}$ is a random number from a uniform distribution [0,1], l=0.005 drives persistence, and $C_{\Delta\theta}$ is the number of consecutive Δθ since θ_0 was restored in line with flow vector. While swim speed is calculated as:

$$\boldsymbol{S_{B\{1\}} = L_f * \left(S_{cruise} + R_{[-0.5,0.5]} * \left(S_{cruise} - S_{drift}\right)\right)} \quad \text{(A - 12)}$$

where, L_f is fish length (m), S_{drift} and S_{cruise} are drift and cruise velocities (body lengths/sec), and $R_{[-0.5,0.5]}$ is uniform distribution [-0.5,0.5].

◇ Behavior B{2}

At the state B{2} (swim toward faster flowing water), when B{2} successfully reduces water acceleration A_M in successive time steps, swim speed $S_{B\{2\}}$ is set in the same manner as $S_{B\{1\}}$. However, if B{2} does not reduce water acceleration, then speed boosts as:

$$S_{B\{2,3,4\}} = V_M * (1 + u_b) \quad \text{(A - 13)}$$

where, V_M is water velocity magnitude and u_b=1.5 is the boost, with $S_{B\{2,3,4\}}$ bounded as $[S_{cruise}, S_{burst}]$ where S_{burst} is burst velocity (body lengths/sec). Water acceleration is interpolated to each X_t and the V_M gradient, for B{2} orientation is based on sensory acuity of ovoid size uniformly distributed between SQD_{min} and SQD_{max}. To determine SQD margin values the following equations are used:

$$SQD_{min} = \frac{\eta}{\log_{10}\left(\frac{A_M}{A_0}\right)} \quad \text{(A - 14)}$$

$$SQD_{max} = SQD_{min} * \left(1 + R_{[0,1]} * \delta\right) \quad \text{(A - 15)}$$

where:

- η → a coefficient used to scale minimum sensory point distance according to Acceleration, with a range 0-10. The value is determined in Agent Behavior Coefficients file, and it is equal to 4.5 in our simulations,
- $\log_{10}\left(\frac{A_M}{A_0}\right)$ → is scaled Acceleration magnitude (A_M) as analogous to the decibel scale. A_M is assumed equal to 0.0001 m/sec^2 (minimum value that affects sensory ovoid size) and A_0 is an arbitrary reference equal to 10^{-6},
- $R_{[0,1]}$ → is from uniform distribution [0,1],
- δ → is the percentage of sensory point distance random increase, ranging from 0.1 to 3. The value is determined in Agent Behavior Coefficients file, and it is equal to 2 in our simulations

◇ Behavior B{3}

The state B{3} (swim against flow vector), is an escape response that decays relatively slowly with time. The slow dissipation of B{3} utility results in the prolonged B{3} behavior after initiation. Initial θ_0 is the direction opposite of the water flow vector, and subsequent moves occur at a persistent Δθ within arc $\alpha_{B\{3\}}=\pm\varepsilon/\text{Log}_{10}(A_M/A_0)$ (xy-plane) and $0.5\alpha_{B\{3\}}$ (vertical) from the inversed water flow vector, where ε = 180°. With this function, allowed deviation from θ_0 is reduced in high acceleration regions where water flow currents might quickly draw fish into high velocity routes and fast, strongly oriented swimming is required for successful escape maneuvers. Persistent Δθ perpetuates unless θ′ exceeds $\alpha_{B\{3\}max}=\pm90°$ or (A - 11). Swim speed $S_{B\{3\}}=S_{burst}$ upon transition to B{3} decays in subsequent time steps as:

$$S_{B\{3\}t} = S_{B\{3\}t-1} * (1 - u_d) \quad \text{(A - 16)}$$

where, u_d=0.025, but does not drop below (A-13) and it is further bounded as $[S_{cruise}, S_{burst}]$.

◇ Behavior B{4}

The state B{4} overrides the vertical swimming component, if necessary, to ensure θ_{0Z} is toward acclimatized pressure (depth) and uses a persistent $\Delta\theta_Z = \pm 0.1^o$, but does not override a more favorable θ_{0Z} component in θ_0, and is not less than the inversed vertical flow vector if travel is leading away from acclimatized pressure (depth). Swim speed preserves a more favorable speed established by B{2,3} or from the prior move and bounded as [S_{cruise}, S_{burst}].

Application 1. Calculation of single fish trajectory

The present application deals with the simulation of a single virtual fish released at specific location in an orthogonal volume (30x10x10 m).

The input data include the following:

1. Geometry
2. Flow data
3. Agent Behavior Coefficients
4. Fish release location

Followed by the calculation regarding the first time to create the Sensory Points and to calculate fish's next position and velocity.

Finally, the trajectory of the virtual fish was presented, while the transition between all four behaviors was discussed.

Application 2. Effect of flow data and seed on single fish trajectory

The application regards different hydraulic and other input data, in order to explore the behavior of the model. Firstly, series of applications are depicted, where included a variety of hydraulic grids (different accelerations and velocities) to assess the respective impact of those alterations. It is highlighted that a section of relatively high accelerations is placed in the middle of the examined geometry, to investigate the effects before and after this surface of accelerations. To facilitate comparison and comprehension reasons one fish with the same release location (Table 5.1 - 1) is used for the different scenarios.

Ceteris paribus, the results are presented concerning different values of acceleration magnitude and water velocities (Table 5.1 - 2). Finally, it is noted that the velocities are presented and denoted only via U velocity as it is the most significant and representative magnitude of velocities.

◇ Effect of acceleration - Scenarios 1, 2, 3 and 4

In scenario 1 (base scenario) the very low values of acceleration ($\sim 10^{-9}$) in combination with the low values of water velocities ($\sim 10^{-5}$) cannot trigger any of the behavior B{2}, B{3} and B{4}. Therefore, the virtual fish moves only by B{1} and exits the calculation domain via the outlet exit route after 272 seconds, as shown in Figure 5.2-1a.

In scenario 2, in which we increase the initial values of accelerations by 1.000 times, the fish follows the same trajectory as in Scenario 1, as shown in Figure 5.2-1b, i.e. its behavior remains unaffected.

In scenario 3, initial accelerations are further increased by 10.000 times, and the virtual fish exits the calculation domain via the outlet section after 356 seconds, following a prolonged movement by 30% compared to scenario 1 (Figure 5.2-1c). This longer trajectory is due to the fact that the specific acceleration magnitude increase triggers behavior B{2}, which drives the fish towards faster water regions.

In scenario 4, initial accelerations are increased by 100.000 times, both behaviors B{2} and B{3} are activated, behavior B{3} prevails and subsequently the fish abandons the downstream migration due to high accelerations, orients upstream and exits the calculation domain via the inlet section (upstream) after 208 seconds (Figure 5.2-1d).

◇ Effect of seed number - Scenarios 5, 6, 7, and 8

Hydraulic data of the base scenario 4 (acceleration ~10^{-4} and velocities ~10^{-5}) are used in combination with altered seed number for scenarios 5, 6, 7 and 8.

In scenario 5, a seed (random number) equal to 200 is used, driving the fish to exit the calculation domain via the outlet section after 526 seconds (Figure 5.3- 2a), in contrast to base scenario where fish oriented upstream. Moreover, no event observed during the movement; the virtual fish moved only by behavior B{1}.

In scenarios 6, 7, and 8 initial seed number changed to 300, 400 and 500 respectively, resulting in fish exiting via the inlet section (upstream), as in base scenario. In all three scenarios behaviors B{2,3} were also involved in fish orientation (Figure 5.3- 2b, c & d). Changes in movement duration (Scenario 6=224 sec, Scenario 7=452 sec and Scenario 8=356 sec) are caused by differences in prevailed behaviors for each scenario.

The most prolonged route is observed in Scenario 7 (Figure 5.3 - 1), which caused by repeated attempts for downstream passage. Fish may evaluate several times the same passage before choose to select or reject it.

◇ Effect of flow velocity - scenarios 9, 10 and 11

In the examination of the effect of flow velocity, scenario 4 (acceleration ~10^{-4} and velocities ~10^{-5}) is used as the base scenario.

In scenario 9 values of water velocities increased by 1.000 times, driving the fish to exit the calculation domain via upstream inlet section after 540 seconds, following a longer trajectory by merely 100% compared to scenario 4. This prolonged trajectory caused by a greater "effort" to continue downstream passage (Figure 5.4 - 1) due to the increased flow velocity, as shown in Figure 5.4-2a. During this scenario behaviors B{1,2,3,4} are involved in fish orientation.

In scenario 10 values of water velocities increased further by 10.000 times. Fish movement was highly influenced as the fish exit the calculation volume via the outlet after 40 seconds; an enormous reduction in movement duration as consequence of high velocities (Figure 5.4-2b). During this scenario behaviors B{1,2,3} are involved.

In scenario 11 values of water velocities increased by 100.000 times; a nonrealistic scenario, used only for comparison and demonstration purposes (Figure 5.4-2c). Every behavior response is eliminated probably due to the fact that perception procedure at these water velocities is impossible. The fish moved solely via B{1} pure "flow convection", exiting the outlet after 5 seconds.

Sensitivity Analysis

Sensitivity analysis calculations have been performed for 100 fishes and 9 scenarios-combinations of velocities-accelerations, which involved 3 scenarios of low, medium and high values of velocities and 3 analogous scenarios of accelerations; these are shown in Table 6 - 1. In all runs, we calculated the number of fishes passing through the outlet. This sensitivity analysis consists of more than 120 runs.

The analysis was performed in 2 steps. In the first step, calculations were performed for the combinations (1) A-LOW and U-MEDIUM and (2) A-HIGH and U-MEDIUM and the results are presented in Table 6 - 2.

From Table 6 - 2 it is depicted that the most sensitive coefficients are coefficient 3, 7 and 16.

In the second step of the analysis, additional calculations were performed for coefficients 3, 7 and 16; all 9 scenarios and the results are depicted in Table 6 - 3.

From the present sensitivity analysis, the following conclusions are drawn:

1. The most important coefficients of the model are coefficients 3, 7 and 16.

2. Coefficient 3 represents the value of utility for behavior B{1}; lower values of utility result in lower participation of behavior B{1} in fish movement and vice versa. Thus if only behavior B{1} is used, downstream passage is unaffected by environmental variables (100% passage result), otherwise impact of environmental variables in downstream migration is undoubted.

3. Coefficient 7 is the memory coefficient for behavior B{3}, integrating the amount of past information into the next decision following the notion that intensity or duration of activity in sensory neurons needs to pass a threshold to reach awareness. Consequently, lower values of memory coefficient lead to more frequent activation of behavior B{3} and vice versa. Hence, prevalence of behavior B{3} leads to significant decrease in passage results, while on the other hand downstream migration enhanced.

4. Coefficient 16 denotes the subjective intrinsic value of behavior B{4} in realizing a goal. Use of minimum value equals to permanent deactivation of this behavior.

Conclusions

The following conclusions are drawn from the present study:

1. The model ELAM is probably the most appropriate model from those available in the literature that can be used for fish modeling purposes in Fish-Passes.

2. A single fish can perceive

    a. stimuli from acceleration change based on "just noticeable differences", and

    b. changes in pressure proportionally to changes in depth.

Following this state, a fish can choose among the below possible behaviors:

a. B{1}, to swim along with the flow; this consists of a Biased Correlated Random Walk (BCRW), in the direction of the flow.

b. B{2}, to swim towards regions of faster flows thus achieving reduction of force exchange, facilitating downstream migration through obstacle avoidance and limiting exposure to turbulence.

c. B{3}, to swim against flow vector, which is an escape response, where fish abandons downstream migration to swim upstream.

d. B{4}, to swim vertically toward acclimatized depth; this orients swimming to acclimatized depth if not already accomplished by other behaviors.

Behaviors B{2,3} are associated with changes in acceleration, while behavior B{4} with changes in pressure.

3. Presence of acceleration cues can trigger behaviors B{2,3}. Significant values of acceleration magnitude are essential to activate those behaviors, however, more important is the role of acceleration gradient in perception of changes.

4. Flow velocity provides no stimuli to the fish, but it can influence its trajectory; high velocities mitigate trajectory fluctuations and facilitate downstream migration.

5. The seed number may have an important effect on fish trajectory; thus, it is advisable to perform the same calculations for various seed numbers.

6. The most important coefficients of the model are coefficients 3, 7 and 16.

   a. Coefficient 3 represents the value of utility for behavior B{1}; lower values of utility result in lower participation of behavior B{1} in fish movement and vice versa.

   b. Coefficient 7 is the memory coefficient for behavior B{3}, integrating the amount of past information into the next decision. Lower values of memory coefficient lead to more frequent activation of behavior B{3} and vice versa.

   c. Coefficient 16 denotes the subjective intrinsic value of behavior B{4} in realizing a goal. Use of minimum value equals to permanent deactivation of this behavior.

Proposed research

The following research is proposed to be extended and applied in Fish-Passes. Actually, this is currently performed in the NTUA in the form of 2 MSc Theses:

1. Development of a fish model based on the present findings and combine with a CFD model to apply it in a river section including a vertical slot Fish-Pass.

2. Development of a fish model based on the present findings and combine with a CFD model to apply it at TUM-Hydro Shaft Power Plant Prototype (Oskar von Miller – Institute, Obernach; Technical University of Munich).

B. ΕΚΤΕΤΑΜΕΝΗ ΠΕΡΙΛΗΨΗ

Σκοπός της παρούσας εργασίας

Ο κύριος σκοπός της παρούσας εργασίας είναι η επιλογή ενός μοντέλου συμπεριφοράς ιχθύων, ικανού να προσομοιώσει σε ένα ολοκληρωμένο επίπεδο, την αντίδραση των ψαριών στο πλήθος το ερεθισμάτων που δέχονται από το περιβάλλον. Για να επιτευχθεί αυτό διενεργήθηκε μια έρευνα στα υφιστάμενα μοντέλα που είναι διαθέσιμα στη διεθνή βιβλιογραφία. Έπειτα έγινε επεξεργασία και ανάλυση των αποτελεσμάτων της έρευνας, ώστε να επιλεγεί το κατάλληλο μοντέλο για χρήση σε διόδους ιχθύων. Σε γενικές γραμμές, το μοντέλο που επιλέχθηκε μπορεί να χαρακτηριστεί ως καινοτόμο στον τομέα του και αναμένεται να συνεισφέρει σημαντικά στην ανάπτυξη και αξιολόγηση νέων εργασιών, ειδικότερα στη χώρα μας όπου ο συγκεκριμένος τομέας είναι σχετικά καινούριος και δεν έχει αναπτυχθεί αρκετά.

Μεθοδολογία και μέρη της εργασίας

Μεθοδολογία

Η παρούσα εργασία αποτελείται από: α) βιβλιογραφική διερεύνηση και κριτική αξιολόγηση για την επιλογή το κατάλληλου μοντέλου, β) περιγραφή και ανάλυση των λειτουργιών και υπολογισμών του επιλεγμένου μοντέλου, γ) εφαρμογή για την παρουσίαση των υπολογισμών της τροχιάς για ένα ψάρι, δ) εφαρμογή για την ανάδειξη της σημασίας των υδραυλικών δεδομένων και του τυχαίου αριθμού στους υπολογισμούς, ε) ανάλυση ευαισθησίας (για 100 ψάρια) για κρίσιμους παράγοντες που συμμετέχουν στο μοντέλο και στ) αξιολόγηση των αποτελεσμάτων της παρούσας εργασίας και προτάσεις για μελλοντική μελέτη.

Έρευνα για υφιστάμενα μοντέλα

Αρχικά διενεργήθηκε μια προκαταρτική έρευνα αφορούσε τη μελέτη των υφιστάμενων μοντέλων στη διεθνή βιβλιογραφία. Από αυτή την έρευνα ξεχώρισαν τα εξής μοντέλα: το μοντέλο των Goodwin et al (2014), το μοντέλο του Abdelaziz (2013), το μοντέλο των Goodwin et al (2006) και το μοντέλο των Haefner and Bowen (2002).

Αφού αναλύθηκαν τα παραπάνω μοντέλα, έγινε επιλογή το πιο κατάλληλου μοντέλου για τους σκοπούς της παρούσας εργασίας. Ειδικότερα, το μοντέλο των Haefner and Bowen, συνδέει τις δυνάμεις που ασκούνται σε ένα ψάρι με τη συμπεριφορά κολύμβησης του μέσω των φυσικών του χαρακτηριστικών (μήκος και μάζα), αγνοώντας τη διαδικασία αντίληψης των ερεθισμάτων από αυτές τις δυνάμεις και τα ευρύτερα περιβαλλοντικά εναύσματα. Στη συνέχεια, το μοντέλο του Abdelaziz συνδυάζει τα υδραυλικά χαρακτηριστικά με την αρχή της ελάχιστης κατανάλωσης ενέργειας, μία μέθοδο διακριτού random-walk και άλλες ειδικές συμπεριφορές ιχθύων, όμως τα προσομοιωμένα αντικείμενα δεν έχουν χρονικά μεταβαλλόμενες συμπεριφορές και επιπλέον το μοντέλο περιορίζεται σε ανεπένδυτα και λεία κανάλια.

Συμπερασματικά το μοντέλο των Goodwin et al (2014) επιλέγει ως το πιο κατάλληλο για την εξυπηρέτηση των στόχων αυτής της εργασίας, αφού λαμβάνει υπόψη τη διαδικασία αντίληψη των εναυσμάτων από τα ψάρια, συνθέτοντας την κίνηση τους ως αποτέλεσμα των ερεθισμάτων αυτών μέσω σε συνδυασμό με έναν παράγοντα τυχαιότητας (biased correlated random-walk). Παράλληλα το μοντέλο αυτό έχει την ικανότητα να αναπαράγει συμπεριφορές που έχουν παρατηρηθεί σε πραγματικές παρατηρήσεις ιχθύων, όπως ότι ένα ψάρι ενδέχεται να απορρίψει επανειλημμένα ένα δρόμο προτού εντέλει εισέλθει ενώ κάποια άλλα ψάρια δεν επιστρέφουν ποτέ μετά την πρώτη απόρριψη.

Πίνακας Β - 1: Σύγκριση μεταξύ των μοντέλων που εξετάστηκαν

	Haefner and Bowen	Abdelaziz	Goodwin et al
Εφαρμογές	Εγκατάσταση συλλογής ιχθύων	Όχι	Σε διόδους ιχθύων από το U.S. Army Corps of Engineers και από άλλους φορείς του δημοσίου ΗΠΑ
Υδροδυναμικό μοντέλο	Όχι – Εισαγωγή από μοντέλο CFD	Όχι – Εισαγωγή από μοντέλο CFD	Όχι – Εισαγωγή από μοντέλο CFD
Individual-Based-Model	Ναι	Ναι	Ναι
Αποτελέσματα	Αποτελέσματα διάβασης της εγκατάστασης	Τροχιά ψαριού	Τροχιά ψαριού και αποτελέσματα διάβασης
Διαστάσεις	2D	3D	3D
Συμπεριφορές κολύμβησης	3	2	4
Επιλογή συμπεριφοράς κολύμβησης	Μια σειρά απλών κανόνων απόφασης	Διαφορετικοί τύποι συμπεριφοράς για ανεπένδυτα και λεία κανάλια	Θεωρεία της αναμενόμενης χρησιμότητας
Ανάδρομη μετανάστευση	Όχι	Ναι	Ναι
Κατάδρομη μετανάστευση	Ναι	Ναι	Ναι
Χρήση εικόνας και βίντεο	Όχι	Ναι	Όχι
Δυνάμεις που ασκούνται στο ψάρι	Ναι	Όχι	Όχι
Αποφυγή εμποδίων	Ναι	Όχι	Ναι
Αποφυγή τύρβης	Όχι	Ναι	Ναι
Κατανάλωση ενέργειας	Ναι	Ναι	Όχι
Random-walk method	Όχι	Ναι	Ναι
Χρονικά-μεταβαλλόμενες συμπεριφορές	Όχι	Όχι	Ναι
Αντίληψη ερεθισμάτων από το περιβάλλον	Όχι	Όχι	Ναι
Εγκλιματισμός	Όχι	Όχι	Ναι
Επιβεβαίωση μέσω πραγματικών παρατηρήσεων	Ναι	Ναι	Ναι
Αναφορές[1]	28	2	112
Διαθεσιμότητα κώδικα	Όχι	Όχι	Ναι[2]

[1] πηγή: Google Scholar
[2] Κατόπιν επικοινωνίας με Δρ. Goodwin

Παρουσίαση του μοντέλου ELAM

Για να γίνει ευκολότερη η κατανόηση αυτού του σύνθετου μοντέλου, παρουσιάστηκε μια εκτεταμένη ανάλυση όλων των στοιχείων του καθώς και δομήθηκε ένα σκαριφηματικό διάγραμμα ροής, βλ. 3.2 (ένα λεπτομερές διάγραμμα ροής θα ήταν εξαιρετικά εκτενές).

Το μοντέλο λαμβάνει ως στοιχεία εισόδου α) γεωμετρικά χαρακτηριστικά, β) τα υδραυλικά χαρακτηριστικά του υπό εξέταση πεδίου (ταχύτητες ροής U, V, και W, και επιταχύνσεις), γ) συντελεστές συμπεριφοράς και δ) την θέση εκκίνησης του ψαριού.

Αρχικά, το μοντέλο αναγνωρίζει τη θέση εκκίνησης του ψαριού στο αντίστοιχο κελί και εν συνεχεία παρεμβάλλει τα υδραυλικά δεδομένα στο χώρο μέσω τρισδιάστατης 4ης τάξης παρεμβολή.

◇ Δημιουργία σημείων αισθητήρων

Για τη δόμηση του ωοειδούς αισθητήρων του ψαριού απαιτούνται 6 ακτίνες αίσθησης που περιβάλλουν το ψάρι (το κέντρο του ψαριού αντιπροσωπεύει το πρώτο σημείο αισθητήρα, έτσι τα υπόλοιπα αριθμούνται από 2-7). Τα σημεία αισθητήρων είναι τοποθετημένα στο χώρο, σε σχέση με το ψάρι, ως εξής:

1. Το κέντρο το ψαριού,
2. (+ X) στην κατεύθυνση που δείχνει το κεφάλι του ψαριού,
3. (- X) στην κατεύθυνση που δείχνει η ουρά του ψαριού,
4. (+ Y) αριστερά από το ψάρι,
5. (- Y) δεξιά από το ψάρι,
6. (+ Z) στην κατεύθυνση πάνω από το ψάρι (παράλληλα στη βαρύτητα),
7. (- Z) στην κατεύθυνση κάτω από το ψάρι (κατεύθυνση της βαρύτητας).

Όλα τα σημεία αισθητήρων (2-7), ορίζονται ως μετατόπιση από τη θέση του ψαριού (1), με μία διαδικασία που απαρτίζεται από: Απόσταση σημείου αισθητήρα (SPDIST), Τυχαία αύξηση της απόστασης του σημείου αισθητήρα (RINC) και Λευκό θόρυβο στα σημεία αισθητήρων από την προσθήκη εύρους διαφοροποίησης σε δευτερεύοντα σημεία (RAND), ως εξής:

$$\boldsymbol{SPDIST} = \frac{\boldsymbol{\eta}}{\boldsymbol{Log_{10}}\left(\frac{\boldsymbol{A_M}}{\boldsymbol{A_0}}\right)} \qquad \text{(B - 1)}$$

$$\boldsymbol{RINC} = \boldsymbol{1} + \boldsymbol{RRR} * \boldsymbol{\delta} \qquad \text{(B - 2)}$$

$$\boldsymbol{RAND} = (\boldsymbol{2} * \boldsymbol{RRR} - \boldsymbol{1}) * \boldsymbol{C_{40}} \qquad \text{(B - 3)}$$

όπου με RRR συμβολίζεται το τυχαίο νούμερο που παράγεται από το αντίστοιχο πρόγραμμα και με C_{40} η προσθήκη εύρους διαφοροποίησης σε δευτερεύοντα σημεία (λαμβάνει τιμή από τα αρχείο συντελεστών συμπεριφοράς). Στον Πίνακας Β - 2 παρουσιάζονται οι υπολογισμοί για τον προσδιορισμό των αντίστοιχων σημείων αισθητήρων.

Πίνακας Β - 2: Σημεία αισθητήρων ως μετατόπιση από τη θέση του ψαριού

Sensory point #2		
Sensory Ovoid X	=	SPDIST * RINC
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	SPDIST * RAND
Sensory point #3		
Sensory Ovoid X	=	-SPDIST * RINC
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	SPDIST * RAND
Sensory point #4		
Sensory Ovoid X	=	SPDIST * RAND
Sensory Ovoid Y	=	SPDIST * RINC
Sensory Ovoid Z	=	SPDIST * RAND

Sensory point #5		
Sensory Ovoid X	=	SPDIST * RAND
Sensory Ovoid Y	=	-SPDIST * RINC
Sensory Ovoid Z	=	SPDIST * RAND
Sensory point #6		
Sensory Ovoid X	=	SPDIST * RAND
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	SPDIST * C_{41} * RINC
Sensory point #7		
Sensory Ovoid X	=	SPDIST * RAND
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	-SPDIST * C_{41} * RINC

όπου με C_{41} συμβολίζεται ο λόγος της απόστασης του σημείου αισθητήρα (από το κέντρο του ψαριού) στο οριζόντιο επίπεδο προς την αντίστοιχη στο κατακόρυφο (αφορά τα σημεία 6 & 7).

◇ 4 Συμπεριφορές

Ο υπολογισμός της τροχιάς του καθώς και της ταχύτητας του ψαριού είναι αποτέλεσμα του συνδυασμού 4 μοναδικών συμπεριφορών:

1. Κολύμβηση στην κατεύθυνση της ροής μέσω ενός παράγοντα τυχαιότητας (Biased Correlated Random Walk, BCRW), συμπεριφορά Β{1}.
2. Κολύμβηση την κατεύθυνση των αυξανόμενων ταχυτήτων ροής, ανεξάρτητα από την κατεύθυνση της ροής, συμπεριφορά Β{2}.
3. Προσωρινή διακοπή της κατάντη μετανάστευσης και κατεύθυνση προς τα ανάντη, συμπεριφορά Β{3}.
4. Κολύμβηση προς το βάθος που έχει πρωτύτερα εγκλιματιστεί, συμπεριφορά Β{4}.

Οι συμπεριφορές Β{1,2,3} είναι αμοιβαία αποκλειόμενες, ενώ η συμπεριφορά Β{4} μπορεί να συνυπάρχει με οποιαδήποτε από τις άλλες 3.

Η προεπιλεγμένη συμπεριφορά είναι η συμπεριφορά Β{1}.

◇ Αντίληψη ενός ερεθίσματος

Για την προσομοίωση της συμπεριφοράς των ιχθύων (διεύθυνση και ταχύτητα), συνδυάζεται ένα μοντέλο συμπεριφοράς με ένα υδροδυναμικό μοντέλο, αναζητώντας διαφορές επιταχύνσεων και πιέσεων, που με τη σειρά τους μπορούν να ενεργοποιήσουν κάποια από τις συμπεριφορές Β{2,3,4}.

Για τη διαδικασία αντίληψης των αλλαγών στις επιταχύνσεις χρησιμοποιείται η αρχή της "*μόλις αισθητής διαφοράς*" του Weber ("*just noticeable difference*"), η οποία επιτρέπει την αλλαγή στην αντίληψη του ίδιου ερεθίσματος μέσα από την εμπειρία.

$$\boldsymbol{E_1(t) = \frac{I_1(t) - I_{\alpha_1}(t)}{I_{\alpha_1}(t)}} \qquad (B - 4)$$

$$\boldsymbol{I_1(t) = \log_{10}\left(\frac{A_M}{A_0}\right)} \qquad (B - 5)$$

$$\boldsymbol{I_{\alpha_1}(t) = \left(1 - m_{a_1}\right) * I_1(t) + m_{a_1} * I_{\alpha_1}(t-1)} \qquad (B - 6)$$

όπου, $I_1(t)$ είναι η αντιληπτή ένταση του εναύσματος της επιτάχυνσης τη χρονική στιγμή t, A_0 είναι σταθερά ίση με 10^{-6}, $I_{\alpha 1}(t)$ αντιληπτή ένταση του εναύσματος της επιτάχυνσης στη οποία το ψάρι έχει εγκλιματιστεί, m_{a1} συντελεστής μεταξύ [0,1] δηλώντας την ταχύτητα με την οποία το ψάρι εγκλιματίζεται σε νέες τιμές έντασης του συγκεκριμένου ερεθίσματος, A_M η επιτάχυνσή τη χρονική στιγμή t ($A_M \geq 2*10^{-6}$). Έτσι, απαιτείται μεγαλύτερη μεταβολή στην αντιληπτή ένταση της επιτάχυνσης όταν η τιμή που έχει εγκλιματιστεί είναι μεγάλη, για να επιτευχθεί το ίδιο αποτέλεσμα.

Εάν το $E_1(t)$ υπερβεί μια τιμή-κατώφλι ίση με $k_{B\{2\}}$ = 0.8373, τότε η συμπεριφορά B{2} ενεργοποιείται, οδηγώντας το ψάρι στην κατεύθυνση των μεγαλύτερων ταχυτήτων ροής. Αντίθετα, αν το $E_1(t)$ υπερβεί μια τιμή-κατώφλι ίση με $k_{B\{3\}}$ = 0.89, τότε η συμπεριφορά B{3} ενεργοποιείται, οδηγώντας το ψάρι να εγκαταλείψει την πορεία προς τα κατάντη και να κινηθεί προς τα ανάντη.

Έχει παρατηρηθεί ότι τα ψάρια εγκλιματίζονται στις νέες πιέσεις (υδροστατική πίεση) με την πάροδο του χρόνου. Εάν η διαφορά μεταξύ της πίεσης στην οποία έχει εγκλιματιστεί και στην τρέχουσα πίεση που δέχεται (τρέχων βάθος), $E_2(t)$, υπερβεί μία τιμή-κατώφλι τότε η συμπεριφορά B{4} ενεργοποιείται, κατευθύνοντας το ψάρι προς το βάθος στο οποίο είχε εγκλιματιστεί.

$$\boldsymbol{E_2(t) = \left|I_2(t) - I_{\alpha_2}(t)\right|} \qquad \text{(B - 7)}$$

όπου, $I_2(t)$ είναι η αντιληπτή ένταση του εναύσματος της πίεσης (δηλαδή το βάθος του ψαριού) τη χρονική στιγμή t και $I_{\alpha 2}(t)$ η αντιληπτή ένταση του εναύσματος της πίεσης στην οποία έχει εγκλιματιστεί, η οποία υπολογίζεται ομοίως από την (B-6).

Εάν το $E_2(t)$ υπερβεί μια τιμή-κατώφλι ίση με $k_{B\{4\}}$ = 1.1315, τότε η συμπεριφορά B{4} ενεργοποιείται, οδηγώντας το ψάρι να κινηθεί προς την κατεύθυνση το βάθους στο οποίο είχε εγκλιματιστεί.

Αν το ψάρι κατευθυνθεί προς την επιφάνεια, τότε ο συντελεστής m_{a2} τροποποιείται ως εξής:

$$\boldsymbol{m_{a_2} = m_{a_2} * C_{38}} \qquad \text{(B - 8)}$$

όπου C_{38} είναι ο συντελεστής μνήμης για τον εγκλιματισμό όταν ψάρι κινείται προς την επιφάνεια, με πιθανό εύρος τιμών: 0.9 ~ 1.0.

◇ Πιθανότητα και χρησιμότητα

Η πιθανότητα και η χρησιμότητα που συνδέονται με το κάθε ερέθισμα υπολογίζονται, ώστε το ερέθισμα με την υψηλότερή τιμή χρησιμότητας, είναι εκείνο στο οποίο αντιδρά το ψάρι τη δεδομένη χρονική στιγμή. Οι αντιληπτές αλλαγές στις επιταχύνσεις, $E_1(t)$, και στις πιέσεις (βάθος), E_2 (t), που υπερβαίνουν τις τιμές-κατώφλι $k_{B\{2,3\}}$ και $k_{B\{4\}}$, αντίστοιχα, ενισχύουν τους συντελεστές που συνδέονται με την κάθε συμπεριφορά B{2,3,4}. Οι άνοδοι και οι πτώσεις στις τιμές της χρησιμότητας συμβαίνουν λόγω των γεγονότων που καταγράφονται. Ένα γεγονός καταγράφεται δίνοντας τιμή $e_B(t)$=1 εάν έχει υπερβληθεί η τιμή-κατώφλι και $e_B(t)$=0 αν όχι, σε κάθε χρονική στιγμή. Η πιθανότητά το ψάρι να απαντήσει με τη συμπεριφορά B{2,3,4}, υπολογίζεται ως εξής:

$$\boldsymbol{P_B(t) = (1 - m_B)e_B(t) + m_B P_B(t-1)} \qquad \text{(B - 9)}$$

όπου ο συντελεστής μνήμης m_B αναπαριστά το ποσοστό της προηγούμενης πληροφορίας που συμμετέχει στη διαδικασία απόφασης της επόμενης, ακολουθώντας το σκεπτικό ότι η ένταση και η διάρκεια μιας δραστηριότητας πρέπει να ξεπεράσουν μία τιμή για να γίνουν αντιληπτές στους αισθητήριους νευρώνες.

Η απόφαση επιλογής της συμπεριφοράς βασίζεται σε μία αντικειμενική συνάρτηση (χρησιμότητα), όπου κάθε πιθανή a συμπεριφορά B{1,2,3,4} σχετίζεται με μία αναμενόμενη χρησιμότητα, U_B (t):

$$U_B(t) = P_B(t)u_B - C_B(t) \qquad \text{(B - 10)}$$

όπου u_B είναι η υποκειμενική εσωτερική τιμή της εκάστοτε συμπεριφοράς στην επίτευξη ενός στόχου, όπως για παράδειγμα στη μείωση της αντιληπτής αλλαγής στις επιταχύνσεις για τις i=1,2, $E_i(t)$. Για λόγους απλοποίησης το κόστος συνειδητοποίησης επίτευξης ενός στόχου λαμβάνεται ίσο με $C_{B\{1,2,3,4\}} = 0$. Η χρησιμότητα της συμπεριφορά Β{1} παραμένει σταθερή στο χρόνο και ίση με $U_{B\{1\}}=0.25$, αλλά οι χρησιμότητες Β{2,3,4} κυμαίνονται καθώς το ψάρι κινείται μέσα στο υδραυλικό πεδίο. Σε κάθε δεδομένη χρονική στιγμή, η συμπεριφορά μεταξύ των Β{1,2,3} με τη μεγαλύτερη χρησιμότητα $U_B(t)$ είναι ενεργή. Η συμπεριφορά Β{4} ενεργοποιείται χωριστά όταν $U_{B\{4\}} \geq \beta u_{B\{4\}}$, όπου β=0.9.

Αυτό το πλαίσιο δημιουργεί συμπεριφορές που κατά μέσο όρο μεγιστοποιούν τη χρησιμότητα, όμως σε μεμονωμένες χρονικές στιγμές μπορεί να εμφανίζονται σαν τυχαίες.

◇ Συμπεριφορά Β{1}

Η συμπεριφορά Β{1} αποτελεί την προεπιλογή για κάθε στιγμή, και συνίσταται στην κολύμβηση στην κατεύθυνση της ροής με έναν παράγοντα τυχαιότητας (biased correlated random walk, BCRW). Η αρχική γωνία θ_0 συμπίπτει με τον δείκτη της ροής και κατευθύνει το ψάρι με μία σταθερή Δθ. Οι τιμές της Δθ λαμβάνονται, ομοιόμορφα κατανεμημένες, από ένα τόξο $\alpha_{B\{1,2\}}=\pm 20^o$ για το οριζόντιο επίπεδο και $0.5\alpha_{B\{1,2\}}$ για το κατακόρυφο. Η εμμονή στην ίδια Δθ συνεχίζεται μέχρι:

$$R_{[0,1]} \leq e^{(l * C_{\Delta\theta})} - 1 \qquad \text{(B - 11)}$$

όπου, $R_{[0,1]}$ είναι ένα τυχαίο νούμερο από την ομοιόμορφη κατανομή [0,1], l=0.005 είναι συντελεστής εμμονής, και $C_{\Delta\theta}$ είναι ο αριθμός των συνεχόμενων επαναλήψεων του ίδιου Δθ από τη στιγμή που εκκίνησε. Παράλληλα η ταχύτητα κολύμβησης υπολογίζεται ως:

$$S_{B\{1\}} = L_f * \left(S_{cruise} + R_{[-0.5,0.5]} * \left(S_{cruise} - S_{drift}\right)\right) \qquad \text{(B - 12)}$$

όπου, L_f είναι το μήκος του ψαριού (m), S_{drift} and S_{cruise} είναι η ταχύτητες συμπαράσυρσης και πλεύσης αντίστοιχα (μήκη σώματος/sec), και $R_{[-0.5,0.5]}$ ένα τυχαίο νούμερο από την ομοιόμορφη κατανομή [-0.5,0.5].

◇ Συμπεριφορά Β{2}

Στη συμπεριφορά Β{2} (κολύμβηση προς τις υψηλότερες ταχύτητες) όταν επιτυγχάνεται συνεχής μείωση των αντιλαμβανόμενων επιταχύνσεων A_M, τότε η ταχύτητα κολύμβησης $S_{B\{2\}}$ υπολογίζεται όπως η Β-12. Ειδάλλως υπολογίζεται ως:

$$S_{B\{2,3,4\}} = V_M * (1 + u_b) \qquad \text{(B - 13)}$$

όπου, V_M είναι η ταχύτητα ροής και $u_b=1.5$ είναι ένας συντελεστής αύξησης. Η ταχύτητα $S_{B\{2,3,4\}}$ οροθετείται μεταξύ $[S_{cruise}, S_{burst}]$ όπου S_{burst} η ταχύτητα έκρηξης.

Οι επιταχύνσεις έχουν παρεμβληθεί στο χώρο και η ταχύτητα ροής V_M βασίζεται στην ακρίβεια του ωοειδούς αισθητήρων, που εκτείνεται από SQD_{min} έως SQD_{max}. Για τον υπολογισμό των οριακών αυτών τιμών χρησιμοποιούνται οι παρακάτω εξισώσεις:

$$SQD_{min} = \frac{\eta}{\log_{10}\left(\frac{A_M}{A_0}\right)} \qquad \text{(B - 14)}$$

$$SQD_{max} = SQD_{min} * \left(1 + R_{[0,1]} * \delta\right) \qquad \text{(B - 15)}$$

όπου:

- η → συντελεστής που χρησιμοποιείται για την κλιμάκωση της ελάχιστης απόστασης σημείου αισθητήρα, με εύρος 0-10. Η τιμή που χρησιμοποιείται στους υπολογισμούς είναι ίση με 4.5,

- $\log_{10}\left(\frac{A_M}{A_0}\right)$ → η κλιμάκωση του μεγέθους της επιτάχυνσης (A_M) σε αναλογία με την κλίμακα decibel. A_M λαμβάνει τη μικρότερη τιμή η οποία επηρεάζει το μέγεθος του ωοειδούς αισθητήρων 0.0001 m/sec^2 ενώ το A_0 είναι μία σταθερά ίση με 10^{-6},

- $R_{[0,1]}$ → ένα τυχαίο νούμερο από την ομοιόμορφη κατανομή [0,1],

- δ → το ποσοστό της τυχαίας αύξησης της απόστασης σημείου αισθητήρα, με εύρος 0.1 έως 3. Η τιμή που χρησιμοποιείται στους υπολογισμούς είναι ίση με 2.

◇ Συμπεριφορά B{3}

Η συμπεριφορά B{3} (κολύμβηση προς τα ανάντη), αποτελεί μια αντίδραση διαφυγής η οποία εξασθενεί σχετικά αργά με το χρόνο. Η αργή μείωση της χρησιμότητας της συμπεριφοράς B{3} οδηγεί σε μία παρατεταμένη χρήση της μετά την ενεργοποίηση. Η αρχική θ_0 είναι σε αντίθετη κατεύθυνση από την ροή και κινείται με σταθερή Δθ εντός ενός τόξου $\alpha_{B\{3\}}=\pm\varepsilon/\text{Log}_{10}(A_M/A_0)$ στο οριζόντιο επίπεδο και $0.5\alpha_{B\{3\}}$ στο κατακόρυφο, όπου ε = 180°. Λόγω της χρήσης αυτής της εξίσωσης η επιτρεπόμενη απόκλιση από την θ_0 φθίνει σε περιοχές υψηλών επιταχύνσεων όπου τα ρεύματα μπορεί να παρασύρουν το ψάρι σε δρόμους υψηλών ταχυτήτων άμεσα, για αυτό απαιτείται επιμονή στην κατεύθυνση για επιτυχή διαφυγή. Η εμμονή στην ίδια Δθ συνεχίζεται έως ότου ξεπεραστεί το $\alpha_{B\{3\}max}=\pm 90^o$ ή (Β - 11). Η ταχύτητα κολύμβησης είναι ίση με $S_{B\{3\}}=S_{burst}$ κατά τη συμπεριφορά B{3} η οποία φθίνει στο χρόνο ως:

$$S_{B\{3\}t} = S_{B\{3\}t-1} * (1 - u_d) \qquad \text{(Β - 16)}$$

όπου, u_d=0.025, αλλά όχι μικρότερο από (Β-13) και οροθετείται περαιτέρω ως [S_{cruise}, S_{burst}].

◇ Συμπεριφορά B{4}

Η συμπεριφορά B{4} επαναπροσδιορίζει την παράγοντα της κατακόρυφης κατεύθυνσης, αν χρειαστεί, ώστε να διασφαλίζει μια γωνία θ_{0Z} με κατεύθυνση προς το βάθος που έχει εγκλιματιστεί, χρησιμοποιώντας μια σταθερή $\Delta\theta_Z$ = ±0.1°. Η ταχύτητα παραμένει όπως είχε προσδιοριστεί από τις συμπεριφορές B{2,3} ή από την προηγούμενη κίνηση και οροθετείται από [S_{cruise}, S_{burst}].

Εφαρμογή 1. Υπολογισμός τροχιάς ενός ψαριού

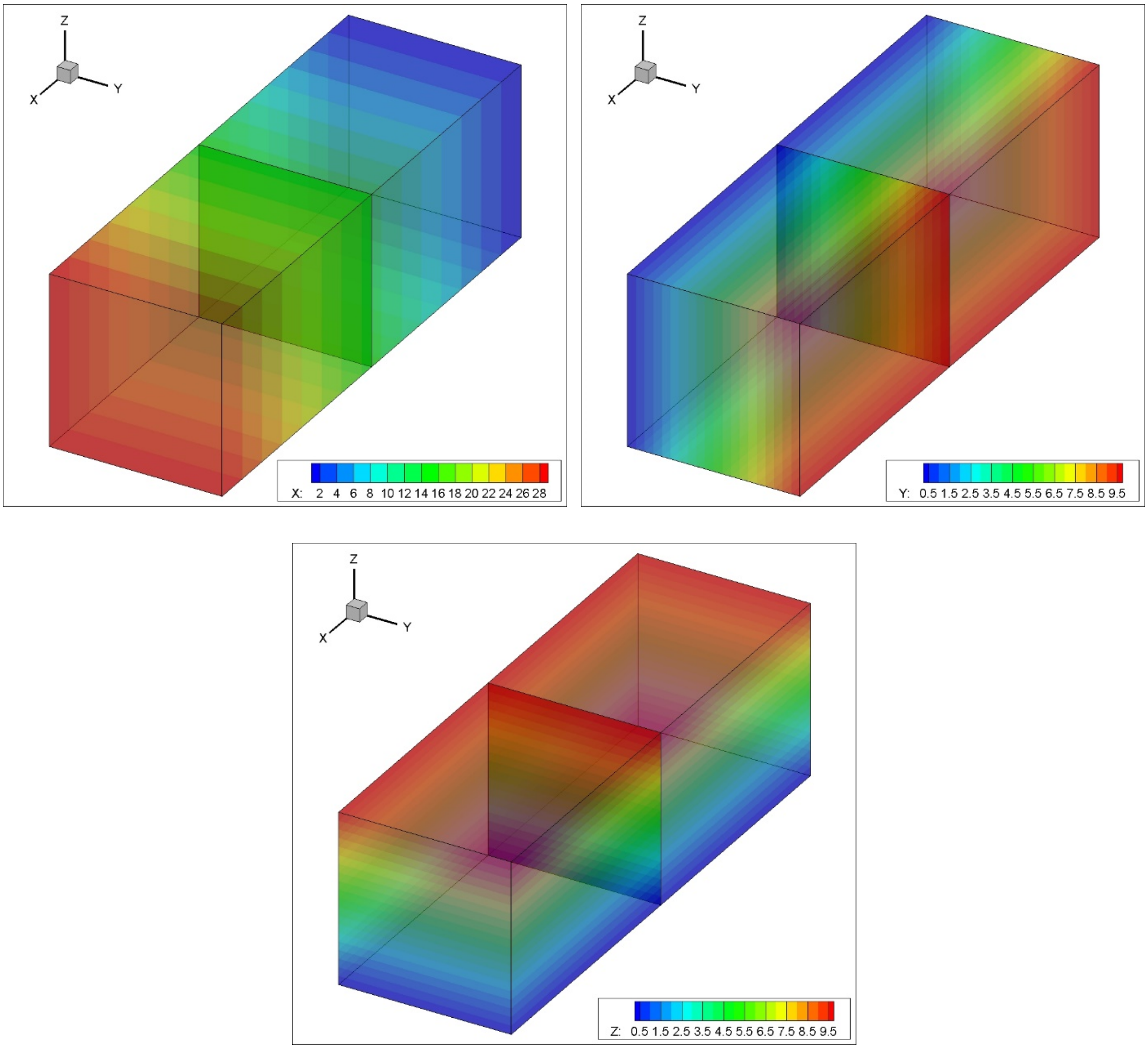
Στην παρούσα εφαρμογή εξετάζεται η προσομοίωση της τροχιάς ενός ψαριού, το οποίο εκκινεί από συγκεκριμένη θέση σε έναν ορθογωνικό όγκο (30x10x10 m).
Τα δεδομένα εισόδου περιλαμβάνουν τα ακόλουθα:

1. Γεωμετρία
2. Υδραυλικά χαρακτηριστικά
3. Συντελεστές συμπεριφοράς
4. Θέση εκκίνησης του ψαριού

◇ Γεωμετρία

Πίνακας Β - 3: Διαστάσεις πλέγματος

Δείκτες	**I**	**J**	**K**
Αριθμός κόμβου	20	15	15
Μήκος σε μέτρα	15	10	10



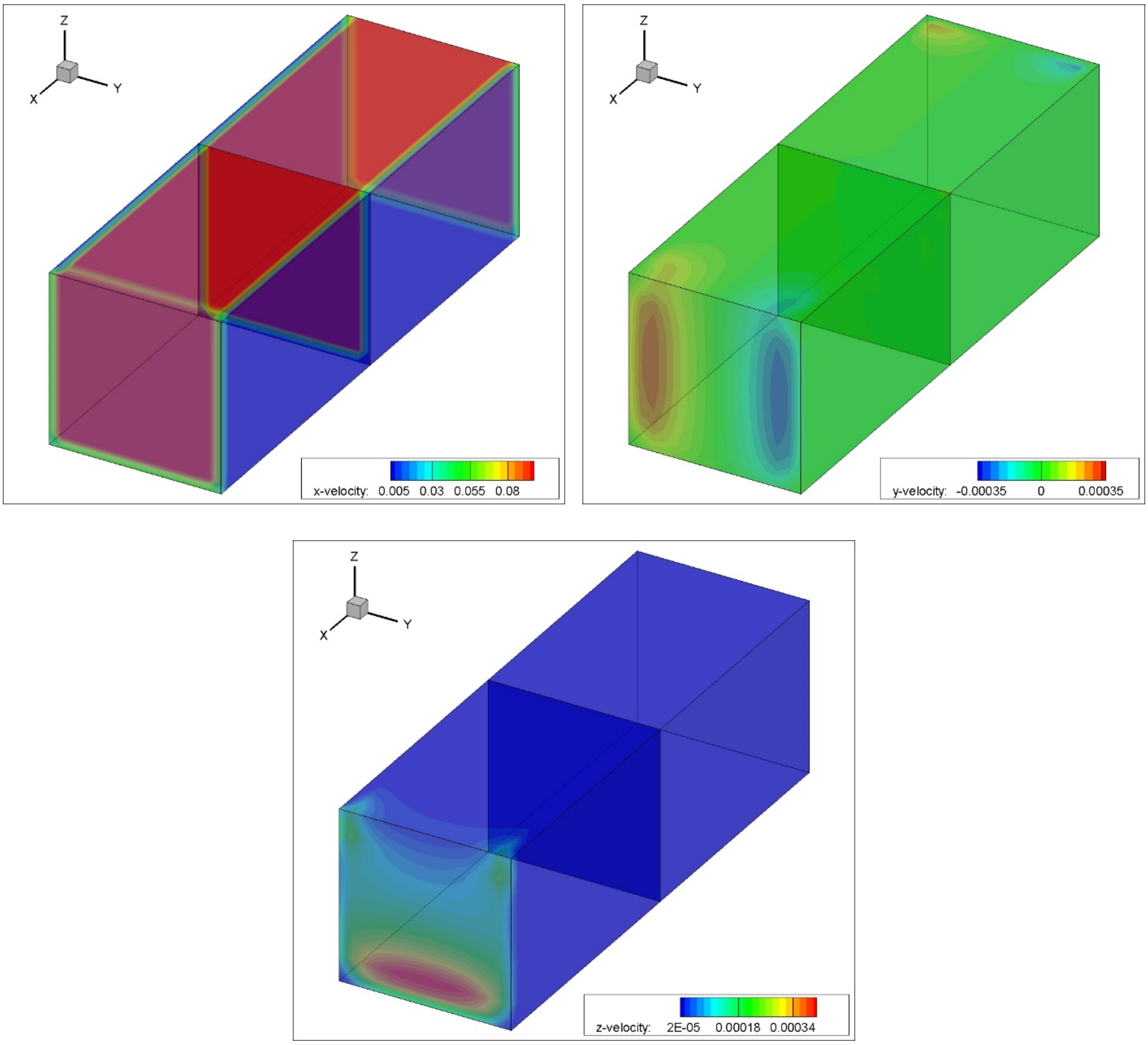
Σχήμα Β - 1: Πλέγμα (X, Y and Z)

◇ Υδραυλικά χαρακτηριστικά

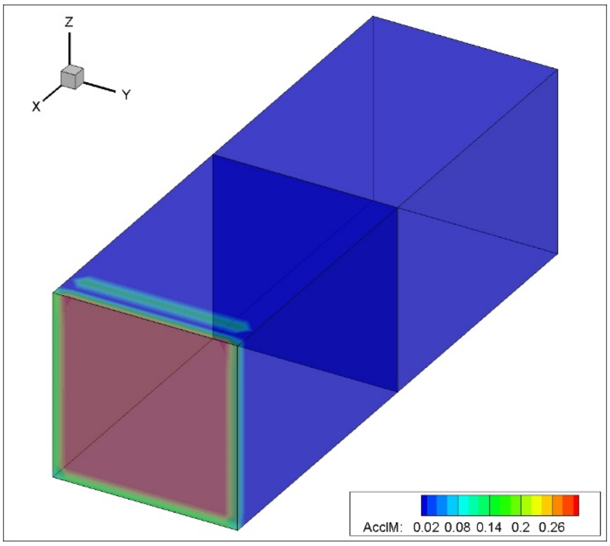
Τα υδραυλικά χαρακτηριστικά που χρησιμοποιούνται στο μοντέλο είναι:

1. Ταχύτητες ροής (U, V and W) σε m/s, και
2. Επιταχύνσεις (A) σε m/s^2.

Επιπλέον, η πίεση λαμβάνεται ίση με την υδροστατική.



Σχήμα Β - 2: Ταχύτητες ροής στην X, Y και Z κατεύθυνση (U, V, και W)



Σχήμα Β - 3: Επιταχύνσεις (Α)

◇ Συντελεστές συμπεριφοράς

Πίνακας Β - 4: Τιμές και περιγραφές συντελεστών συμπεριφοράς

Όνομα	Τιμή	Εύρος τιμών	Περιγραφή
C_1	4.5	0.5-10.0	***η***
C_2	200.0	10.0-300.0	***δ*** (διαιρείται με 100 μόλις εισάγεται)
C_3	0.25	0.001-0.999	Τιμή πιθανότητας για το πρώτο time step. Έπειτα γίνεται η τιμή χρησιμότητας για τη συμπεριφορά Β{1}
C_4	8	-	Πλήθος παραγόντων, χρησιμοποιούνται μόνο οι 4 από τους 8
C_5	1	-	Συντελεστής μνήμης για τη συμπεριφορά Β{1}
C_6	0	0.0-1.0	Συντελεστής μνήμης για τη συμπεριφορά Β{2}
C_7	0.9985	0.0-1.0	Συντελεστής μνήμης για τη συμπεριφορά Β{3}
C_8	0.9	0.0-1.0	Συντελεστής μνήμης για τη συμπεριφορά Β{4}
C_{13}	1	-	Εσωτερική χρησιμότητα για τη συμπεριφορά Β{1}
C_{14}	0.5	0.0-1.0	Εσωτερική χρησιμότητα για τη συμπεριφορά Β{2}
C_{15}	1	0.0-1.0	Εσωτερική χρησιμότητα για τη συμπεριφορά Β{3}
C_{16}	1	0.0-1.0	Εσωτερική χρησιμότητα για τη συμπεριφορά Β{4}
C_{21}	0	-	Τιμή-κατώφλι Β{1}
C_{22}	0.8373	-	Τιμή-κατώφλι Β{2}
C_{23}	0.89	-	Τιμή-κατώφλι Β{3}
C_{24}	1.1315	-	Τιμή-κατώφλι Β{4}
C_{29}	0	-	Συντελεστής μνήμης για την ανανέωση του εγκλιματισμού συμπεριφορά Β{1}
C_{30}	0.9999	0.0-1.0	Συντελεστής μνήμης για την ανανέωση του εγκλιματισμού συμπεριφορά Β{2}
C_{31}	0	-	Συντελεστής μνήμης για την ανανέωση του εγκλιματισμού συμπεριφορά Β{3}
C_{32}	0.9984	0.0-1.0	Συντελεστής μνήμης για την ανανέωση του εγκλιματισμού συμπεριφορά Β{4}
C_{37}	0.9	0.0-1.0	**β**
C_{39}	0	-	Αλληλεπίδραση παραγόντων (1=Ναι, 0=Όχι)
C_{40}	0	0.0-1.0	Προσθήκη εύρους διαφοροποίησης σε δευτερεύοντα σημεία

C_{41}	1	0.0-1.0	Λόγος της απόστασης του σημείου αισθητήρα (από το κέντρο του ψαριού) στο οριζόντιο επίπεδο προς την αντίστοιχη στο κατακόρυφο (αφορά τα σημεία 6 & 7).
C_{42}	0.4	0.4-1.0	Χαμηλότερη τιμή όριο για τον αρχικό εγκλιματισμό σε επιτάχυνση
C_{44}	0.005	0.0-0.7	**/**

◇ Θέση εκκίνησης του ψαριού

Πίνακας Β - 5: Θέση εκκίνησης ψαριού, Εφαρμογή 1

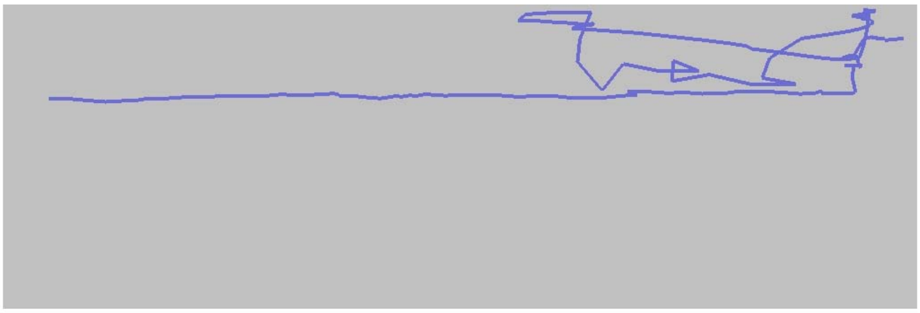
Δείκτες	**X**	**Y**	**Z**
Τιμή εισόδου	1.5	5.0	-3.0
Τιμή στο μοντέλο	1.5	5.0	6.9

Οι τιμές Z είναι αρνητικές συμβολίζοντάς την απόσταση από την ελεύθερη επιφάνεια. Η τιμή μειώνεται κατά 0.1 μ ως προσέγγιση της υπερύψωσης της στάθμης.

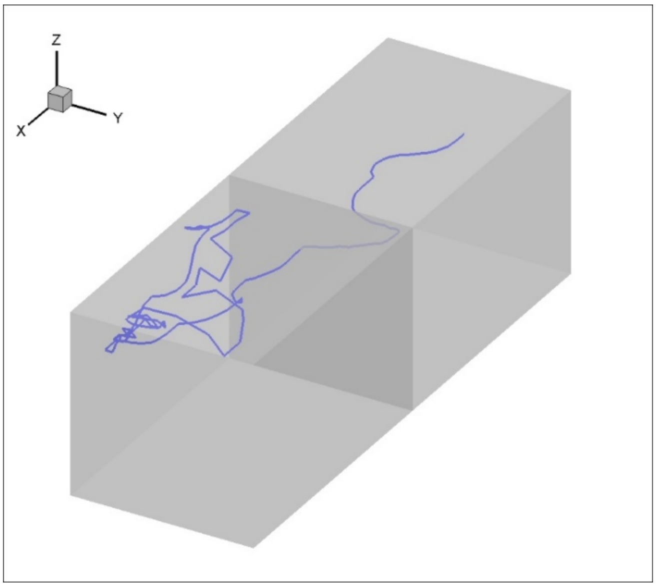
Στη συνέχεια ακολουθούν οι υπολογισμοί που αφορούν με τη δημιουργία σημείων αισθητήρων και τον προσδιορισμό της επόμενη θέση και ταχύτητας του ψαριού (βλ. 4.3)

Τέλος, παρουσιάζεται η τροχιά του εικονικού ψαριού, ενώ ταυτόχρονα περιγράφεται η μετάβαση μεταξύ των τεσσάρων συμπεριφορών (βλ. 4.4)

Κάτοψη



Πλάγια όψη



3D όψη

Σχήμα Β - 4: Τροχιά ψαριού, Εφαρμογή 1

Εφαρμογή 2. Επίδραση των υδραυλικών δεδομένων και τυχαίων αριθμών που χρησιμοποιούνται στους υπολογισμούς στην τροχιά ενός ψαριού

Η εφαρμογή αφορά διαφορετικά υδραυλικά και άλλα δεδομένα εισόδου, για να διερευνήσει τη συμπεριφορά του μοντέλου. Αρχικά απεικονίζεται μία σειρά από εφαρμογές, όπου περιέχει ένα εύρος υδραυλικών χαρακτηριστικών (διαφορετικές επιταχύνσεις και ταχύτητες), για να αξιολογήσει την αντίστοιχη επίπτωση των μεταβολών αυτών. Επισημαίνεται ότι ένα τμήμα σχετικά υψηλών επιταχύνσεων τοποθετήθηκε στη μέση του εξεταζόμενου όγκου, για να διερευνηθούν οι επιδράσεις πριν και μετά από αυτήν την επιφάνεια των επιταχύνσεων. Για να επιτευχθεί καλύτερη σύγκριση και κατανόηση, χρησιμοποιήθηκε ίδια θέση εκκίνησης για το ένα ψάρι σε όλα τα διαφορετικά σενάρια.

Πίνακας Β - 6: Θέση εκκίνησης ψαριού, Εφαρμογή 2

Δείκτες	**X**	**Y**	**Z**
Τιμή εισόδου	1.5	1.5	-1.0
Τιμή στο μοντέλο	1.5	1.5	8.9

Διατηρώντας τους υπόλοιπους παράγοντες ίδιους, παρουσιάζονται τα αποτελέσματα που αφορούν διαφορετικές τιμές μεγέθους επιταχύνσεων και ταχυτήτων (Πίνακας Β - 7). Τέλος, σημειώνεται ότι οι ταχύτητες που παρουσιάζονται, αντιπροσωπεύονται μόνο μέσω των U, καθώς είναι η πιο σημαντική ταχυτήτων (ως μέγεθος).

Πίνακας B - 7: Σενάρια που εξετάσθηκαν

	Επιταχύνσεις (m/s^2)		Τυχαίος αριθμός	Ταχύτητες (m/s)	
	Mean	Max		Mean	Max
Scenario 1	1.21E-10	3.06E-09	100	9.92E-05	1.01E-04
Scenario 2	1.21E-07	3.06E-06	100	9.92E-05	1.01E-04
Scenario 3	1.21E-06	3.06E-05	100	9.92E-05	1.01E-04
Scenario 4	1.21E-05	3.06E-04	100	9.92E-05	1.01E-04
Scenario 5	1.21E-05	3.06E-04	200	9.92E-05	1.01E-04
Scenario 6	1.21E-05	3.06E-04	300	9.92E-05	1.01E-04
Scenario 7	1.21E-05	3.06E-04	400	9.92E-05	1.01E-04
Scenario 8	1.21E-05	3.06E-04	500	9.92E-05	1.01E-04
Scenario 9	1.21E-05	3.06E-04	100	9.92E-02	1.01E-01
Scenario 10	1.21E-05	3.06E-04	100	9.92E-01	1.01
Scenario 11	1.21E-05	3.06E-04	100	9.92*	10.1*

*μη ρεαλιστικές τιμές, χρησιμοποιούνται μόνο για λόγους σύγκρισης και επίδειξης.

◇ Η επίδραση της επιτάχυνσης- Σενάρια 1, 2, 3 και 4

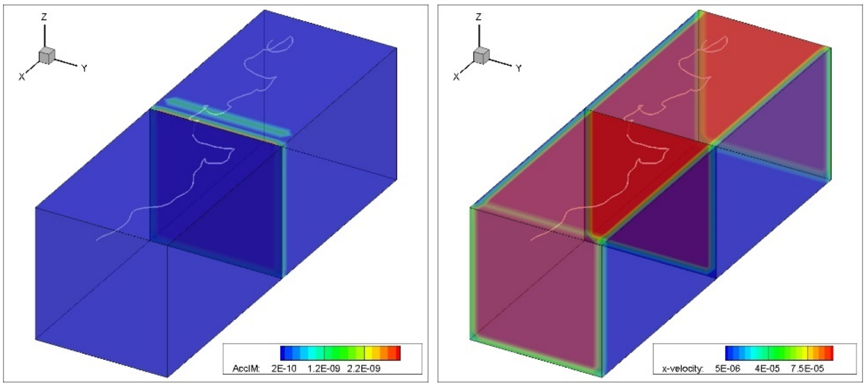
Στο πρώτο σενάριο (βασικό σενάριο) οι πολύ χαμηλές τιμές της επιτάχυνσης ($\sim10^{-9}$) σε συνδυασμό με τις χαμηλές τιμές της ταχύτητας του νερού ($\sim10^{-5}$) δεν μπορούν να προκαλέσουν κάποια από τις συμπεριφορές B{2}, B{3} και B{4}. Συνεπώς, το εικονικό ψάρι κινείται μόνο από B{1} και εξέρχεται από τον τομέα υπολογισμού μέσω της εξόδου μετά από 272 δευτερόλεπτα, όπως φαίνεται στο Σχήμα B - 5a.

Στο δεύτερο σενάριο, στο οποίο αυξάνουμε τις αρχικές τιμές των επιταχύνσεων κατά 1.000, το ψάρι ακολουθεί την ίδια τροχιά όπως στο πρώτο σενάριο, όπως φαίνεται στο Σχήμα B - 5b, δηλαδή η συμπεριφορά του παραμένει ανεπηρέαστη.

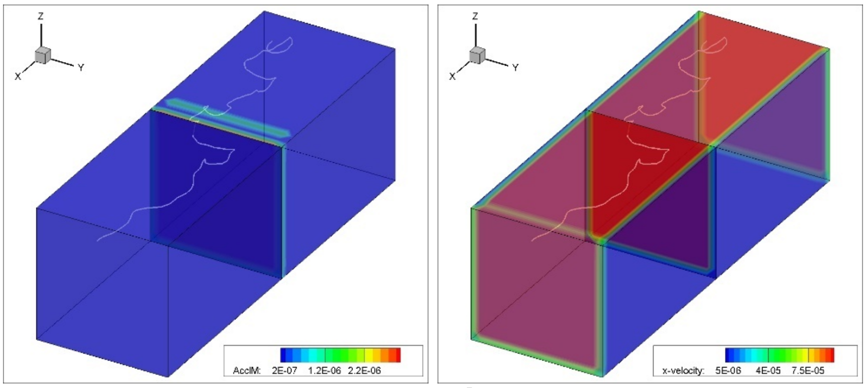
Στο τρίτο σενάριο, οι αρχικές επιταχύνσεις αυξάνονται περαιτέρω κατά 10.000 φορές, όπου το εικονικό ψάρι εξέρχεται από τον τομέα υπολογισμού μέσω της εξόδου μετά από 356 δευτερόλεπτα, ακολουθώντας μία παρατεταμένη κίνηση κατά 30% συγκριτικά με το πρώτο σενάριο (Σχήμα B - 5c). Αυτή η μεγαλύτερη τροχιά οφείλεται στο γεγονός ότι η συγκεκριμένη αύξηση του μεγέθους της επιτάχυνσης διέγειρε την συμπεριφορά B{2}, η οποία οδηγεί το ψάρι σε ταχύτερες ροές.

Στο τέταρτο σενάριο, οι αρχικές επιταχύνσεις αυξήθηκαν κατά 100.000 φορές, όπου οι συμπεριφορές B{2} και B{3} ενεργοποιήθηκαν. Με την συμπεριφορά B{3} να επικρατεί τα ψάρια εγκαταλείπουν την κατάντη μετανάστευση λόγω των υψηλών επιταχύνσεων, ακολουθώντας προσανατολισμό προς τα ανάντη. Τελικά εξήλθε από τον όγκο υπολογισμού μέσω του τμήματος εισόδου (ανάντη) μετά από 208 δευτερόλεπτα (Σχήμα B - 5d).

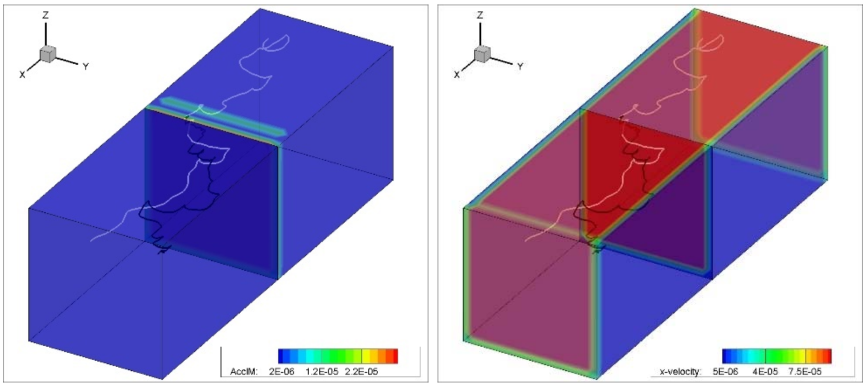
Με μαύρο χρώμα συμβολίζεται η τροχιά του τρέχοντος σεναρίου, ενώ με άσπρο του βασικού σεναρίου.



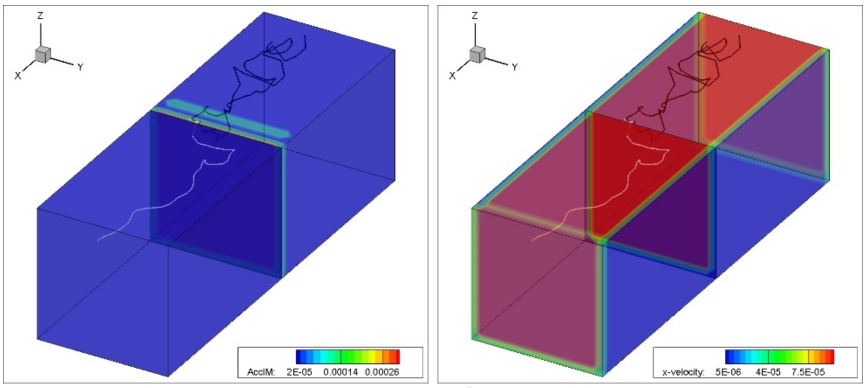
(a)Σενάριο 1



(b)Σενάριο 2



(c)Σενάριο 3



(d)Σενάριο 4

Σχήμα Β - 5: Αποτελέσματα υπολογισμών, επίδραση επιταχύνσεων (Σενάρια 1, 2, 3 και 4)

◇ Επίδραση τυχαίου αριθμού που χρησιμοποιείται στους υπολογισμούς - Σενάρια 5, 6, 7, και 8

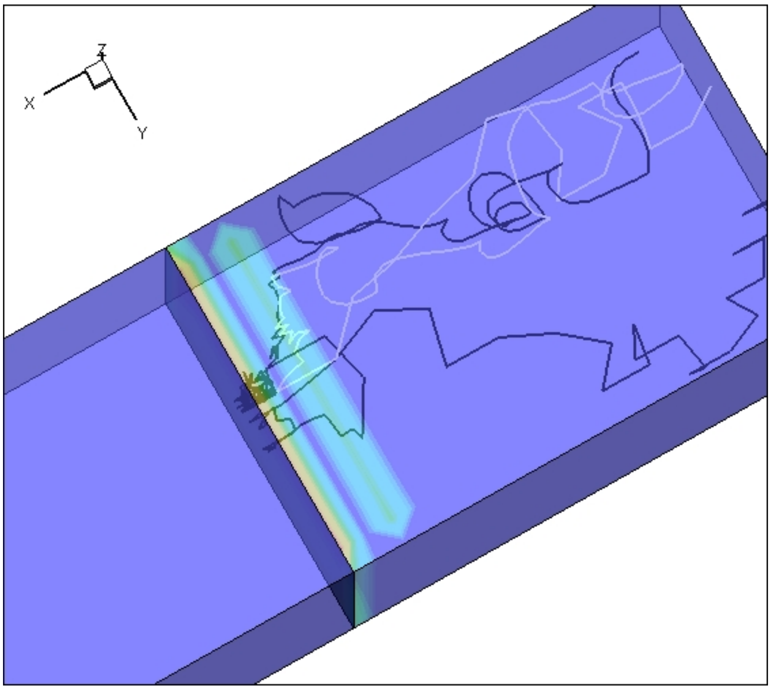
Τα υδραυλικά δεδομένα από το βασικό σενάριο 4 (επιτάχυνση ~10^{-4} και ταχύτητα ~10^{-5}) χρησιμοποιούνται σε συνδυασμό με διάφορες τιμές για τον τυχαίο αριθμό που χρησιμοποιείται στους υπολογισμούς για τα σενάρια 5,6,7 και 8.

Στο πέμπτο σενάριο, χρησιμοποιείται ένας τυχαίος αριθμός ίσος με το 200, οδηγώντας το ψάρι προς την έξοδο από το πεδίο υπολογισμού μέσω του τμήματος εξόδου μετά από 526 δευτερόλεπτα (Σχήμα Β - 7a), σε αντίθεση με το βασικό σενάριο όπου το ψάρι προσανατολίστηκε ανάντη. Επιπλέον, δεν παρατηρείται κανένα γεγονός κατά την διάρκεια της κίνησης που να εγείρει όποια συμπεριφορά, άρα το εικονικό ψάρι μετακινείται μόνο από την συμπεριφορά B{1}.

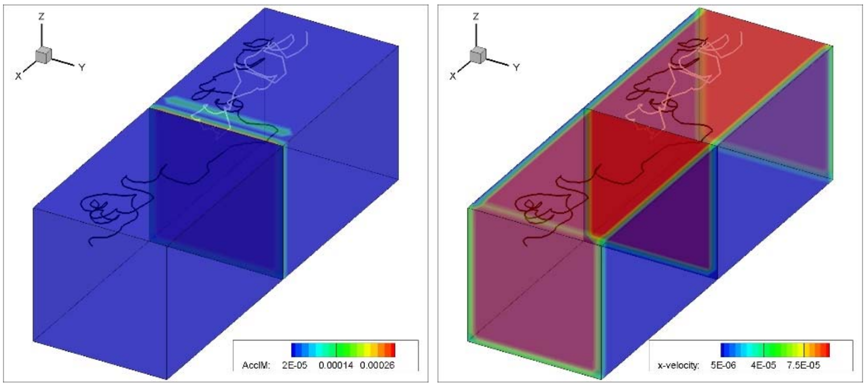
Στα σενάρια 6, 7, και 8 ο αρχικός τυχαίος αριθμός που χρησιμοποιείται στους υπολογισμούς τροποποιήθηκε σε 300, 400 και 500 αντίστοιχα, με αποτέλεσμα το ψάρι να εξέλθει μέσω της εισόδου (ανάντη), όπως και στο βασικό σενάριο. Και στα τρία σενάρια οι συμπεριφορές B{2,3} συμμετείχαν στον προσανατολισμό του ψαριού (Σχήμα Β - 7b, c & d). Οι αλλαγές στην διάρκεια της κίνησης (Σενάριο 6=224 δευτερόλεπτα, Σενάριο 7=452 δευτερόλεπτα και Σενάριο 8=356 δευτερόλεπτα) προκλήθηκαν από τις διαφορές στις επικρατούσες συμπεριφορές για κάθε σενάριο.

Η πιο παρατεταμένη διαδρομή παρατηρείται στο έβδομο σενάριο, η οποία προκλήθηκε από τις επανειλημμένες προσπάθειες για μεταβεί στα κατάντη. Τα ψάρια μπορεί να αξιολογήσουν αρκετές φορές το ίδιο πέρασμα πριν να επιλέξουν να το δεχτούν ή να το απορρίψουν.

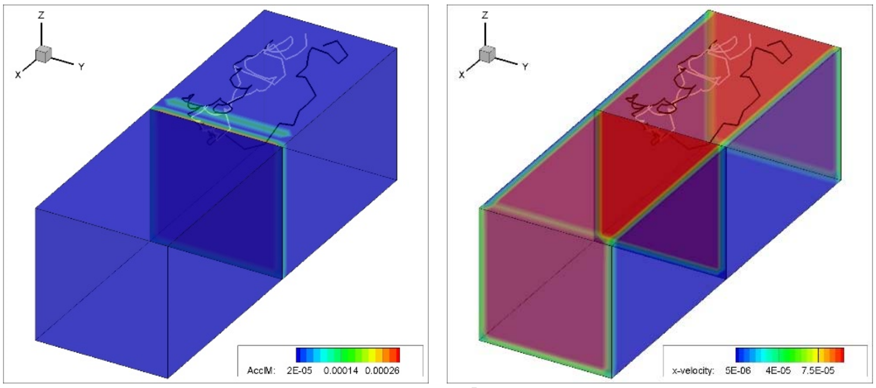
Με μαύρο χρώμα συμβολίζεται η τροχιά του τρέχοντος σεναρίου, ενώ με άσπρο του βασικού σεναρίου.



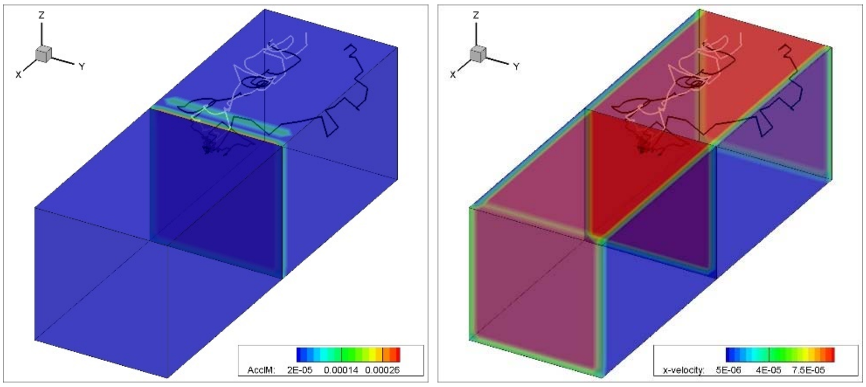
Σχήμα Β - 6: Επανειλημμένες προσπάθειες για κατάντη μετάβαση, Σενάριο 7



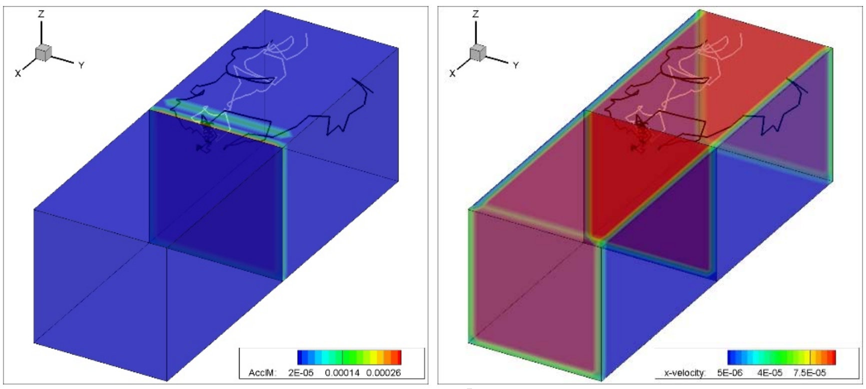
(a)Σενάριο 5



(b)Σενάριο 6



(c)Σενάριο 7



(d)Σενάριο 8

Σχήμα Β - 7: Αποτελέσματα υπολογισμών, επίδραση τυχαίου αριθμού (Σενάρια 5, 6, 7 και 8)

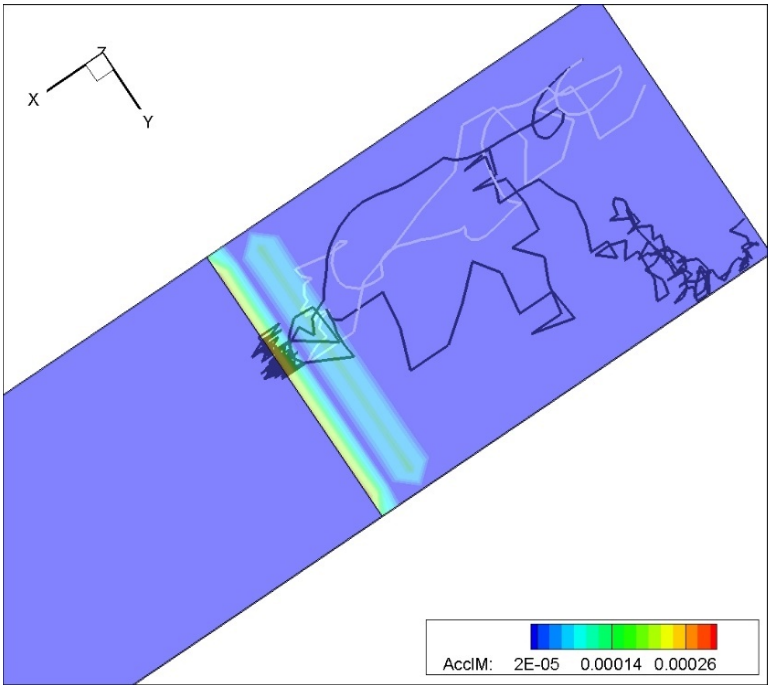
◇ Επίδραση της ταχύτητας ροής- Σενάρια 9, 10 και 11

Για την εξέταση της επίδρασης της ταχύτητας ροής, χρησιμοποιείται το σενάριο 4 (επιτάχυνση ~10^{-4} και ταχύτητα ~10^{-5}) ως βασικό σενάριο.

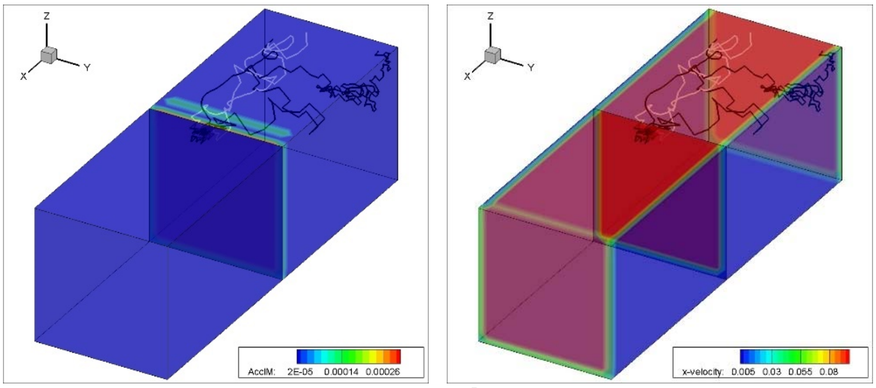
Στο ένατο σενάριο οι τιμές των ταχυτήτων ροής αυξήθηκαν κατά 1.000 φορές, οδηγώντας το ψάρι προς την έξοδο από τον όγκο υπολογισμού μέσω της εισόδου ανάντη μετά από 540 δευτερόλεπτα, ακολουθώντας μια μεγαλύτερη τροχιά κατά 100% συγκριτικά με το τέταρτο σενάριο. Αυτή η παρατεταμένη τροχιά προκλήθηκε από μία επανειλημμένη προσπάθεια του ψαριού να συνεχίσει την κατάντη πορεία (Σχήμα Β - 8) λόγω της αυξημένης ταχύτητας ροής, όπως φαίνεται στο Σχήμα Β - 9a. Κατά την διάρκεια αυτού του σεναρίου, όλες οι συμπεριφορές Β{1,2,3,4} ενεργοποιήθηκαν στον προσανατολισμό του ψαριού.

Στο δέκατο σενάριο οι τιμές των ταχυτήτων του νερού αυξήθηκαν περαιτέρω κατά 10.000 φορές. Η κίνηση του ψαριού επηρεάζεται σε μεγάλο βαθμό, καθώς εξήλθε από τον όγκο υπολογισμού μέσω της εξόδου μετά από 40 δευτερόλεπτα, το οποίο αποτελεί μία τεράστια μείωση της διάρκειας κινήσεως ως συνέπεια των υψηλών ταχυτήτων (Σχήμα Β - 9b). Κατά την διάρκεια αυτού του σεναρίου ενεργοποιήθηκαν οι συμπεριφορές Β{1,2,3}.

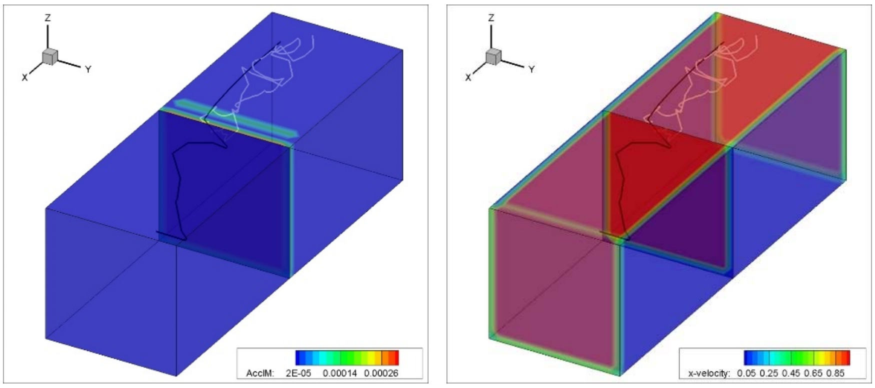
Στο ενδέκατο σενάριο οι τιμές ταχυτήτων του νερού αυξήθηκαν κατά 100.000 φορές, ένα μη ρεαλιστικό σενάριο, το οποίο χρησιμοποιήθηκε μόνο για λόγους σύγκρισης και επίδειξης (Σχήμα Β - 9c). Κάθε αντίδραση εξαλείφεται πιθανόν λόγω του ότι η διαδικασία αντίληψης είναι αδύνατη σε αυτές τις ταχύτητες ροής. Το ψάρι κινήθηκε αποκλειστικά μέσω Β{1} μόνο μετάβαση μέσω ροής, αποχωρώντας από την έξοδο μετά από 5 δευτερόλεπτα.



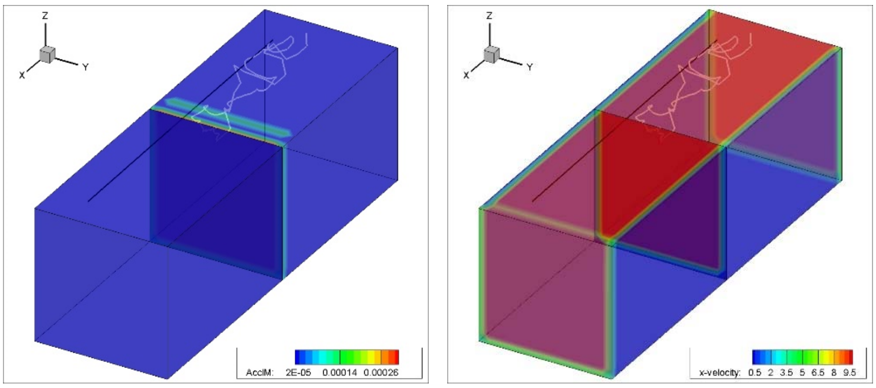
Σχήμα Β - 8: Επανειλημμένες προσπάθειες για κατάντη μετάβαση, Σενάριο 9



(a)Σενάριο 9



(b)Σενάριο 10



(c)Σενάριο 11

Σχήμα Β - 9: Αποτελέσματα υπολογισμών, επίδραση ταχύτητας ροής (Σενάρια 9, 10 και 11)

Ανάλυση ευαισθησίας

Οι υπολογισμοί της ανάλυσης ευαισθησίας πραγματοποιήθηκαν για 100 ψάρια και 9 σενάρια-συνδυασμούς ταχυτήτων-επιταχύνσεων, όπου συμμετέχουν 3 σενάρια χαμηλών, μεσαίων και υψηλών τιμών ταχυτήτων και 3 ανάλογα σενάρια επιταχύνσεων, τα οποία παρουσιάζονται στον Πίνακας Β - 8 . Σε όλες τις περιπτώσεις, υπολογίσαμε τον αριθμό των ψαριών που διέρχονται από την έξοδο. Η ανάλυση ευαισθησίας αποτελείται από περισσότερα από 120 περιπτώσεις.

Πίνακας Β - 8: Τιμές ταχυτήτων και επιταχύνσεων για τα 9 σενάρια

	Επιταχύνσεις (m/s^2)			Ταχύτητες (m/s)	
	Mean	**Max**		**Mean**	**Max**
A-LOW	0.003	0.102	U-LOW	0.034	0.101
A-MEDIUM	0.008	0.306	U-MEDIUM	0.068	0.202
A-HIGH	0.024	0.919	U-HIGH	0.101	0.303

Η ανάλυση πραγματοποιήθηκε σε 2 βήματα. Στο πρώτο βήμα, εκτελέσθηκαν οι υπολογισμοί που αφορούν τους συνδυασμούς (1) A-LOW and U-MEDIUM και (2) A-HIGH and U-MEDIUM, όπου τα αποτελέσματα παρουσιάζονται στον Πίνακας Β - 9.

Πίνακας Β - 9: Αποτελέσματα κατάντη μετάβασης για τους συνδυασμούς (1) A-LOW and U-MEDIUM και (2) A-HIGH and U-MEDIUM

		A-LOW and U-MEDIUM			A-HIGH and U-MEDIUM		
Συντελεστής		**Pass**	**Return**	**Still active**	**Pass**	**Return**	**Still active**
Default		100	0	0	99	1	0
Coefficient 1	0.5	100	0	0	99	1	0
	10.0	100	0	0	97	3	0
Coefficient 2	10.0	100	0	0	100	0	0
	300.0	100	0	0	99	1	0
Coefficient 3	0.001	59	41	0	7	93	0
	0.999	100	0	0	100	0	0
Coefficient 6	1.0	100	0	0	100	0	0
Coefficient 7	0.0	80	0	20	82	0	18
	1.0	100	0	0	100	0	0
Coefficient 8	0.0	100	0	0	99	1	0
	1.0	100	0	0	99	1	0
Coefficient 14	0.0	100	0	0	100	0	0
	1.0	100	0	0	99	1	0
Coefficient 15	0.0	100	0	0	100	0	0
Coefficient 16	0.0	96	4	0	88	12	0
Coefficient 30	0.0	100	0	0	99	1	0
Coefficient 32	0.0	100	0	0	99	1	0
	1.0	100	0	0	97	3	0
Coefficient 40	1.0	100	0	0	99	1	0

Από τον Πίνακας Β - 9 παρουσιάζονται οι περισσότερο ευαίσθητοι συντελεστές, οι οποίοι είναι οι συντελεστές 3, 7 και 16.

Στο δεύτερο στάδιο της ανάλυσης, πραγματοποιήθηκαν επιπλέον υπολογισμοί για τους συντελεστές 3, 7 και 16. Τα αποτελέσματα και των 9 σεναρίων απεικονίζονται στον Πίνακας Β - 10.

Πίνακας Β - 10: Αποτελέσματα κατάντη μετάβασης για όλα τα σενάρια

Default	**A-LOW**	**A-MEDIUM**	**A-HIGH**
U-LOW	100	91	79
U-MEDIUM	100	100	99
U-HIGH	100	100	98
Coef.3-Min			
U-LOW	48	23	4
U-MEDIUM	59	36	7
U-HIGH	72	61	22
Coef.3-Max			
U-LOW	100	100	100
U-MEDIUM	100	100	100
U-HIGH	100	100	100
Coef.7-Min			
U-LOW	24	27	30
U-MEDIUM	80	83	82
U-HIGH	100	100	100
Coef.7-Max			
U-LOW	99	92	77
U-MEDIUM	100	100	100
U-HIGH	100	100	100
Coef.16-Min			
U-LOW	84	74	83
U-MEDIUM	96	93	88
U-HIGH	98	97	99

Από την παρούσα ανάλυση ευαισθησίας, τα παρακάτω συμπεράσματα εξάχθηκαν:

1. Οι σημαντικότεροι συντελεστές του μοντέλου είναι οι συντελεστές 3, 7 και 16.

2. Ο συντελεστής 3 αντιπροσωπεύει την αξία της χρησιμότητας για την συμπεριφορά B{1}. Οι χαμηλότερες τιμές της χρησιμότητας οδηγούν στην μείωση της συμμετοχής της συμπεριφοράς B{1} στην κίνηση των ψαριών και το αντίστροφο. Συνεπώς, αν χρησιμοποιείται μόνο η συμπεριφορά B{1}, η κατάντη μετάβαση δεν επηρεάζεται από περιβαλλοντικές μεταβλητές (100% πέρασμα), διαφορετικά οι επιπτώσεις των περιβαλλοντικών μεταβλητών στην κατάντη μετανάστευση είναι αναμφίβολες.

3. Ο συντελεστής 7 είναι ο συντελεστής μνήμης για την συμπεριφορά B{3}, ενσωματώνοντας το ποσό των τελευταίων πληροφοριών στην επόμενη απόφαση ακολουθώντας την αντίληψη ότι η ένταση ή η διάρκεια της δραστηριότητας στους αισθητικούς νευρώνες χρειάζεται να ξεπεράσει μια κατώτατη τιμή για να γίνουν αντιληπτές. Κατά συνέπεια, οι χαμηλότερες τιμές του συντελεστή μνήμης οδηγούν σε πιο συχνή ενεργοποίηση της συμπεριφοράς B{3} και το αντίστροφο. Ως εκ τούτου, η επικράτηση της συμπεριφοράς B{3} οδηγεί σε σημαντική μείωση στα αποτελέσματα περάσματος, ενώ από την άλλη πλευρά ενισχύεται η κατάντη μετανάστευση.

4. Ο συντελεστής 16 δηλώνει την υποκειμενική εσωτερική αξία χρησιμότητας της συμπεριφοράς B{4} στην υλοποίηση ενός στόχου. Η χρήση της ελάχιστης τιμής ισοδυναμεί με την μόνιμη απενεργοποίηση αυτής της συμπεριφοράς.

Συμπεράσματα

Τα ακόλουθα συμπεράσματα προέκυψαν από την παρούσα μελέτη:

1. Το μοντέλο που επιλέχθηκε (ELAM) αποτελεί ίσως το πιο κατάλληλο, από τα υφιστάμενα στη βιβλιογραφία, για χρήση σε προσομοίωση ιχθύων, όπως για παράδειγμα σε διόδους ιχθύων.

2. Ένα ψάρι μπορεί να αντιληφθεί

    a. Ερεθίσματα από αλλαγές στις επιταχύνσεις με βάση την αρχή της "*μόλις αισθητής διαφοράς*", και

    b. Ερεθίσματα από αλλαγές στην πίεση ανάλογα με τις εναλλαγές στο βάθος.

Ακολουθώντας αυτές τις αρχές, ένα ψάρι μπορεί να επιλέξει μεταξύ των παρακάτω πιθανών συμπεριφορών:

a. B{1}, κολύμβηση προς την κατεύθυνση της ροής. Αποτελείται από την κολύμβηση στην κατεύθυνση της ροής σε συνδυασμό με έναν παράγοντα τυχαιότητας (Biased Correlated Random Walk, BCRW).

b. B{2}, κολύμβηση προς υψηλότερες ταχύτητες ροής, εξασφαλίζοντας μείωση των εναλλαγών στις δυνάμεις που το ασκούνται, διευκόλυνση της κατάντη μετανάστευσης μέσω της αποφυγής εμποδίων και τον περιορισμό έκθεσης σε τύρβη.

c. B{3}, κολύμβηση αντίθετα στην κατεύθυνση της ροής, όπου συνιστά μια αντίδραση διαφυγής κατά την οποία το ψάρι εγκαταλείπει προσωρινά την κατάντη μετανάστευση και στρέφεται προς τα ανάντη.

d. B{4}, κολύμβηση προς το βάθος που έχει εγκλιματιστεί. Κατευθύνει το ψάρι προς το βάθος στο οποίο έχει προγενέστερα εγκλιματιστεί, εάν δεν έχει ήδη επιτευχθεί από τις άλλες συμπεριφορές.

Οι συμπεριφορές B{2,3} σχετίζονται με αλλαγές στις επιταχύνσεις, ενώ η συμπεριφορά B{4} με αλλαγές στην πίεση.

3. Η παρουσία ερεθισμάτων επιτάχυνσης μπορεί να προκαλέσει τις συμπεριφορές B{2,3}. Σημαντικές τιμές του μεγέθους της επιτάχυνσης είναι απαραίτητες για την ενεργοποίηση των συμπεριφορών αυτών, όμως σημαντικότερο ρόλο στην διαδικασία αντίληψης αλλαγών διαδραματίζει η κλίση των επιταχύνσεων.

4. Οι ταχύτητες ροής δεν δημιουργούν ερεθίσματα που αν σχετίζονται με τις συμπεριφορές των ιχθύων, όμως μπορούν να επηρεάσουν σημαντικά την τροχιά του ψαριού. Οι υψηλές ταχύτητες ροής περιορίζουν τις διακυμάνσεις στις τροχιές των ψαριών και διευκολύνουν την κατάντη μετανάστευση.

5. Ο τυχαίος αριθμός που χρησιμοποιείται στους υπολογισμούς μπορεί να έχει επίδραση στην τροχιά του ψαριού. Ως εκ τούτου συνιστάται η εκτέλεση των ίδιων υπολογισμών για διάφορους τυχαίους αριθμούς.

6. Οι σημαντικότεροι συντελεστές του μοντέλου είναι οι συντελεστές 3, 7 και 16.

   a. Ο συντελεστής 3 αντιπροσωπεύει την αξία της χρησιμότητας για την συμπεριφορά B{1}. Οι χαμηλότερες τιμές της χρησιμότητας οδηγούν στην μείωση της συμμετοχής της συμπεριφοράς B{1} στην κίνηση των ψαριών και το αντίστροφο. Συνεπώς, αν χρησιμοποιείται μόνο η συμπεριφορά B{1}, η κατάντη μετάβαση δεν επηρεάζεται από περιβαλλοντικές μεταβλητές (100% πέρασμα), διαφορετικά οι επιπτώσεις των περιβαλλοντικών μεταβλητών στην κατάντη μετανάστευση είναι αναμφίβολες.

   b. Ο συντελεστής 7 είναι ο συντελεστής μνήμης για την συμπεριφορά B{3}, ενσωματώνοντας το ποσό των τελευταίων πληροφοριών στην επόμενη απόφαση ακολουθώντας την αντίληψη ότι η ένταση ή η διάρκεια της δραστηριότητας στους αισθητικούς νευρώνες χρειάζεται να ξεπεράσει μια κατώτατη τιμή για να γίνουν αντιληπτές. Κατά συνέπεια, οι χαμηλότερες τιμές του συντελεστή μνήμης οδηγούν σε πιο συχνή ενεργοποίηση της συμπεριφοράς B{3} και το αντίστροφο. Ως εκ τούτου, η επικράτηση της συμπεριφοράς B{3} οδηγεί σε σημαντική μείωση στα αποτελέσματα περάσματος, ενώ από την άλλη πλευρά ενισχύεται η κατάντη μετανάστευση.

   c. Ο συντελεστής 16 δηλώνει την υποκειμενική εσωτερική αξία της συμπεριφοράς B{4} στην υλοποίηση ενός στόχου. Η χρήση της ελάχιστης τιμής ισοδυναμεί με την μόνιμη απενεργοποίηση αυτής της συμπεριφοράς.

Προτεινόμενη έρευνα

Η έρευνα προτείνεται να επεκταθεί και να εφαρμοστεί σε διόδους ιχθύων. Συγκεκριμένα, ήδη στα πλαίσια αυτά πραγματοποιούνται δύο Μεταπτυχιακές Εργασίες στο ΕΜΠ:

1. Ανάπτυξη μοντέλου προσομοίωσης ιχθύων με βάση τα ευρήματα της παρούσας εργασίας και συνδυασμός του με μοντέλο CFD για την εφαρμογή σε τμήμα ποταμού που συμπεριλαμβάνει δίοδο ιχθύων με vertical slot.
2. Ανάπτυξη μοντέλου προσομοίωσης ιχθύων με βάση τα ευρήματα της παρούσας εργασίας και συνδυασμός του με μοντέλο CFD για την εφαρμογή στο TUM-Hydro Shaft Power Plant Prototype (Oskar von Miller – Institute, Obernach; Technical University of Munich).

Σχήμα Β - 10: Δίοδος ιχθύων με vertical slot (αριστερά), TUM-Hydro Shaft Power Plant Prototype (δεξιά), [source: (FAO, 2001), (Rutschmann, et al., 2016)

1 INTRODUCTION

1.1 Background

Human population has exerted an extensive alteration on river systems to facilitate its needs such as water supply, energy, transportation and protection. Globally, more than 50,000 large dams – capable of holding back about the 15% of total annual river runoff (Nilsson, et al., 2005), countless smaller dams and other hydraulic structures fragment rivers and affect significantly their ecosystems and continuity. The latter, coupled with other factors, drastically threatens fish population in rivers.

Since the beginning of 20th century efforts have been made to develop fishway designs in laboratory, followed by extensive efforts in the middle of the previous century. Merely all the attempts were focused on salmonids species, where salvage regulations encountered from, even, the 19th century in Europe and North America. New legislation procedures, globally (EU Water Framework Directive, 2000; Canadian Species at Risk Act, 2002), during the past decades have renewed the interest in the field and led to new efforts for effective fish passage structures design (Katopodis & Williams, 2012).

Hence the design of fish passes has arisen as a medium to mitigate human impact. These structures facilitate both upstream and downstream migration by restoring longitudinal connectivity. The effectiveness of a fish pass constitutes to the ease of fish finds the entrance and negotiate it without delay, stress or injury that might prejudice the success of their migration (Larinier, 2002).

Although there has been significant progress in successful implementation of fish passes for anadromous migration, catadromous migration still remains a difficult task (Cuchet, 2014). Dam provide generally three different passage routes: a) via turbines, b) via spillway and c) through specifically designed fish passes. These three alternatives differ significantly in mortality effects on fish, constituting of highly importance to understand the way that fishes select their routes. Unfortunately, why some fish enter routes engineered for their safe travel while others choose more dangerous routes is poorly understood (Goodwin, et al., 2014).

In order to deal with this issue, development of fish behavior model is proposed as a manner to alleviate high mortality rates by designing more effectives structures. The latter stems from the idea that, in general, fish may use a specific navigation strategy while migrating, affected by a variety of factors concerning environmental and biological stimuli. Through behavior modeling it is attempted not only to design more effective fish passes, but also to guide the fish to select the safer medium while migrating.

1.2 Scope of the present work

In the present work, a background research review on existing, available fish behavior models in the literature was conducted to identify a fish behavior model that is appropriate in Fish Passes. 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". Specifically, it is comprising the Literature survey n. 3 which dealing with the identification of fish models that are appropriate for Fish Passes, including those that are applied also in other areas.

1.3 Contents

Subsequent to the introduction, eight chapters structure the present work:

- **Chapter 2** presents the literature review conducted along with a critical discussion on the models and selection of the most suitable.
- **Chapter 3** describes every aspect of the selected model in order to highlight the features of supremacy and the way that the model executes fish movement calculations.
- **Chapter 4** illustrates route and the respective calculations regarding an application of single fish.
- **Chapter 5** describes the effects of flow data and seed number on single fish calculations.
- **Chapter 6** consists of a sensitivity analysis for critical components of the model, performed for 100 fishes.
- **Chapter 7** summarizes and discusses the results of this study.

2 BACKGROUND RESEARCH

2.1 General

The preliminary work consists of a background research of fish behavior models in the contemporary literature. The most sophisticated models found are present below; the model of Goodwin et al is presented for two editions as it has evolved significantly over the past decade.

2.2 The model of Goodwin et al (2014)

Goodwin et al (2014) developed a behavioral model, which in combination with a CFD model can simulate fish swim behavior (speed and orientation), as consequence of water acceleration and pressure (depth). The model is calibrated with observed data regarding juvenile Pacific salmonids at seven dams of Columbia /Snake River system, across 47 flow field conditions sampled over 14 years. The present work constitutes the most recent edition of an ever-evolved model; see 2.4.

To overcome monitoring of all environmental and internal factors that affect fish movement in real scale systems, the model is based on three fundamental assumptions: a) despite fluctuation in factors involved the fish movement is hydraulically mediated, b) despite fish can detect hydraulic changes in sub body length scales, much smaller than CFD resolution, these hydraulic data are important to fish as it moves and experiences acceleration and decelerations where water velocities change (spatial acceleration) providing sense analogous to flow field heterogeneity, and c) fish evaluate signals in relative terms so may change their response after repeated exposure. Additionally, Weber's *"just noticeable difference"* is used to allow changes in perception of the same stimulus (water acceleration) through experience.

$$\boldsymbol{E_1(t)} = \frac{\boldsymbol{I_1(t) - I_{\alpha_1}(t)}}{\boldsymbol{I_{\alpha_1}(t)}} \qquad (2.2 - 1)$$

$$\boldsymbol{I_{\alpha_1}(t)} = \left(\boldsymbol{1 - m_{a_1}}\right) * \boldsymbol{I_1(t)} + \boldsymbol{m_{a_1}} * \boldsymbol{I_{\alpha_1}(t-1)} \qquad (2.2 - 2)$$

where, $I_1(t)$ is perceived intensity of a stimulus at the individual's position at time t, $I_{\alpha 1}(t)$ is perceived intensity of that stimulus to which the individual is acclimatized, m_{a1} is a coefficient within [0,1] scaling how quickly the individual acclimatizes to new intensities of the stimulus.

The fish movement hypothesis relies on the assumption that river's bathymetry as well as embedded objects influence flow field patterns which fish follows to navigate. In the present model, three mutually exclusive behavior states, each with a unique swimming orientation, guide the fish movement, i.e:

1. A Biased Correlated Random Walk (BCRW) in the direction of downstream flow, behavior state B{1}.
2. Swimming in the direction leading to faster water, irrespective of the flow direction, behavior state B{2}.
3. Temporal abandonment of downstream migration and upstream swimming orientation, behavior state B{3}.

The default behavior state is B{1}, when environmental cues are detected other behavior states can activate. Specifically, if the fish experience changes in accelerations, different from its recent past two behavior responses can be triggered B{2,3}. As mentioned B{2} orients fish to faster water. The latter is associated with reduction of inertial stimuli of flow pulsation and turbulence, close to obstacles water's edge. Moreover behavior B{2} facilitates downstream migration through obstacle avoidance, and limits exposure to turbulence which is associated with poor swimming efficiency and reduction in predator detection. The behavior B{3} leads to desertion of downstream migration and upstream swimming. The behavioral responses to stimuli and the respective selection of behavioral states are presented in Figure 2.2 - 2.

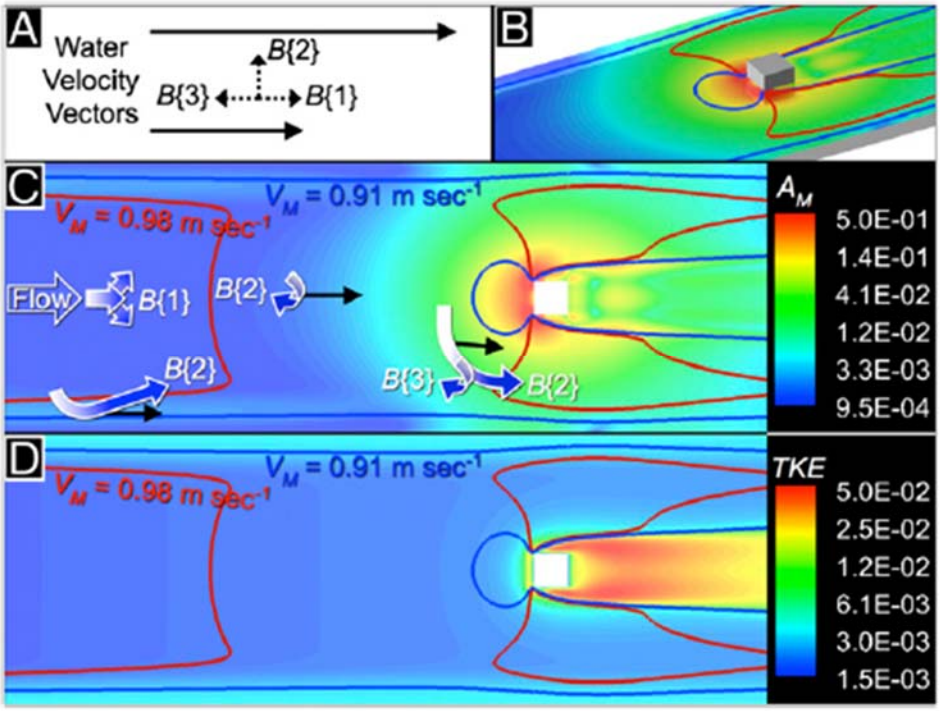


Figure 2.2 - 1: Behavior responses to hydraulic patterns [source: (Goodwin, et al., 2014)]

Some fish species possess a sensitive to pressure swim bladder, so vertical orientation is separated and taken in to account in this model as changes in pressure experienced. Fish acclimatize to new pressure over time; if difference between acclimatized depth and fish elevation, $E_2(t)$, exceeds a threshold value, B{4} is triggered orienting fish to acclimatized depth.

$$\boldsymbol{E_2(t) = \left|I_2(t) - I_{\alpha_2}(t)\right|} \qquad (2.2 - 3)$$

where, $I_2(t)$ is perceived intensity of Pressure stimulus at the individual's position at time t (i.e. the depth), $I_{\alpha 2}(t)$ is perceived intensity of Pressure stimulus to which the individual is acclimatized, also derived from (2.2-2).

Hence, totally 4 behavior states that govern fish orientation in this model. All 4 behaviors depend on fish's unique experience in space and time, while acclimatization integrates past conditions. To describe behavioral transition and duration an event-based decision model is used, tracking each expected utility. The rise and fall in utility occur through Boolean events, taking values equal to 1 when threshold values are exceeded and o otherwise. Probability, $P_B(t)$, of responding with B{j}, j=2,3,4 increases as:

$$\boldsymbol{P_B(t) = (1 - m_B)e_B(t) + m_B P_B(t-1)} \qquad (2.2 - 4)$$

where memory coefficient m_B integrates the amount of past information into the next decision following the notion that intensity or duration of activity in sensory neurons needs to pass a threshold to reach awareness.

The behavior decision is based on an objective function, utility, where each decision in the set of alternatives B{1,2,3,4} has an associated expected utility, U_B (t):

$$\boldsymbol{U_B(t) = P_B(t)u_B - C_B(t)} \qquad (2.2 - 5)$$

where u_B is the subjective intrinsic value of behavior B{j} in realizing the goal, i.e., reduction of perceived change in stimulus i=1,2, $E_i(t)$, to back within the threshold tolerance. For simplicity, cost incurred whether or not the goal is realized is set as $C_{B\{1,2,3,4\}} = 0$. Utility of B{1} is fixed over time as $U_{B\{1\}}=0.25$, but utilities of B{2,3,4} fluctuate as the fish transits the flow field. In an increment of time, the behavior B{1,2,3} with highest utility $U_B(t)$ is active. Separately encoded vertical movement B{4} is implemented when $U_{B\{4\}} \geq \beta u_{B\{4\}}$ where β=0.9.

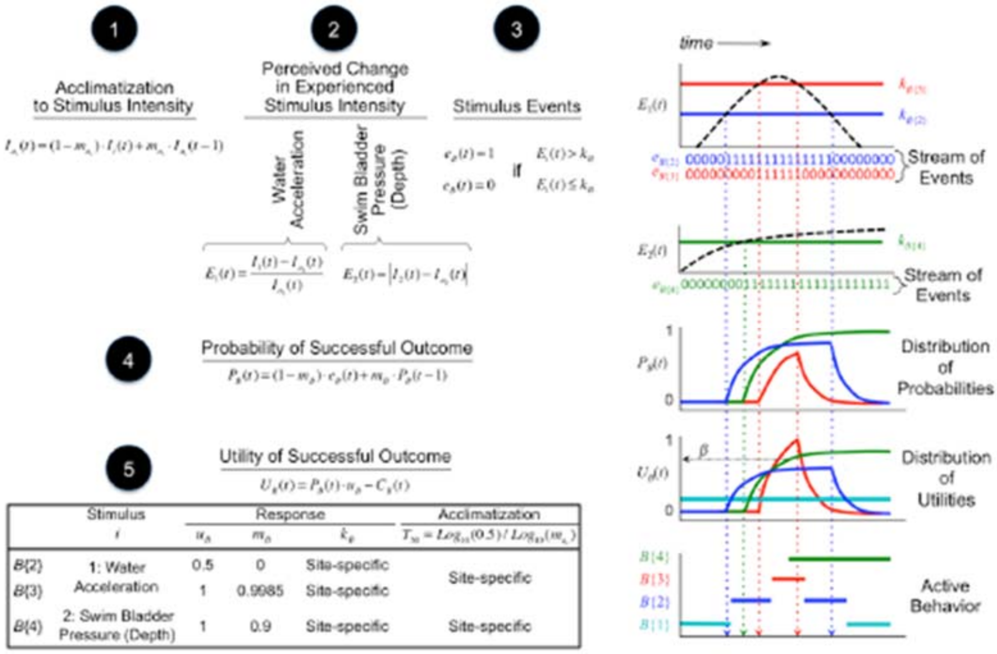


Figure 2.2 - 2: Steps in decision process, transition between behaviors [source: (Goodwin, et al., 2014)]

This framework generates behaviors that, on average, maximize utility but, at any given time, may appear to be random.

Several hypothetical scenarios (different combinations of the behaviors) were examined via the program to facilitate comparison with observed data. The results indicate the use of the full model at sites exhibiting greater flow range or where hydraulic complexity results from an engineered structure. Additionally, the general model captures common patterns of fish passing through routes they previously rejected multiple times and shows how velocity attraction works.

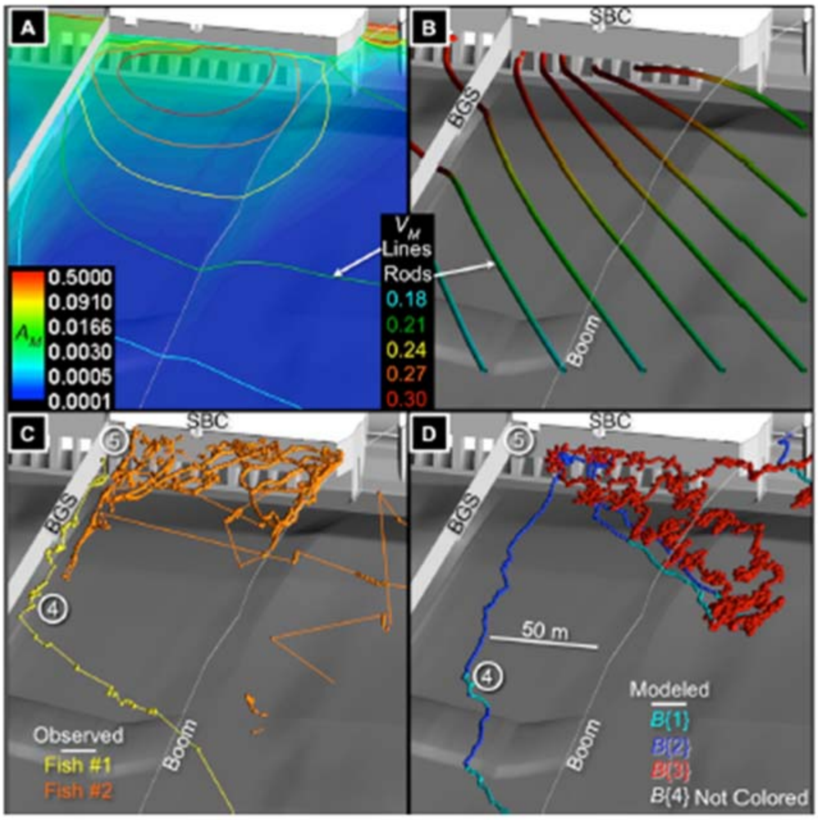


Figure 2.2 - 3: Model-generated fish path in comparison with observed fish movement [source: (Goodwin, et al., 2014)]

2.3 The model of Abdelaziz (2013)

Abdelaziz (2013) developed a numerical model for decoding fish movement patterns through culverts and other fish passages. The model distinguishes between roughened channels, where fish have to swim through them in one go with their burst speeds (one of three types of swimming velocities, which can be maintained for less than 20 seconds), and pool-type channels, where high speeds occur only through the openings of the boulder bars. Therefore, presented two different models for each case.

The model relied on water velocity fields and turbulent flow characteristics, which can be obtained from the observed data or applying a computational fluid dynamics (CFD) code. In addition, "it releases a number of simulated fish and tracks their movements using a concept of minimum energy expenditure, with a discrete random-walk method and other special fish behaviors. The simulated particles do not have time-varying attributes (other than location) which affect their simulated behavioral responses."

• Model for fish movement though a roughened channel with almost uniform main flow directions

The flowchart summarizes the basic structure of the model proposed, then the main steps of the procedure are presented.

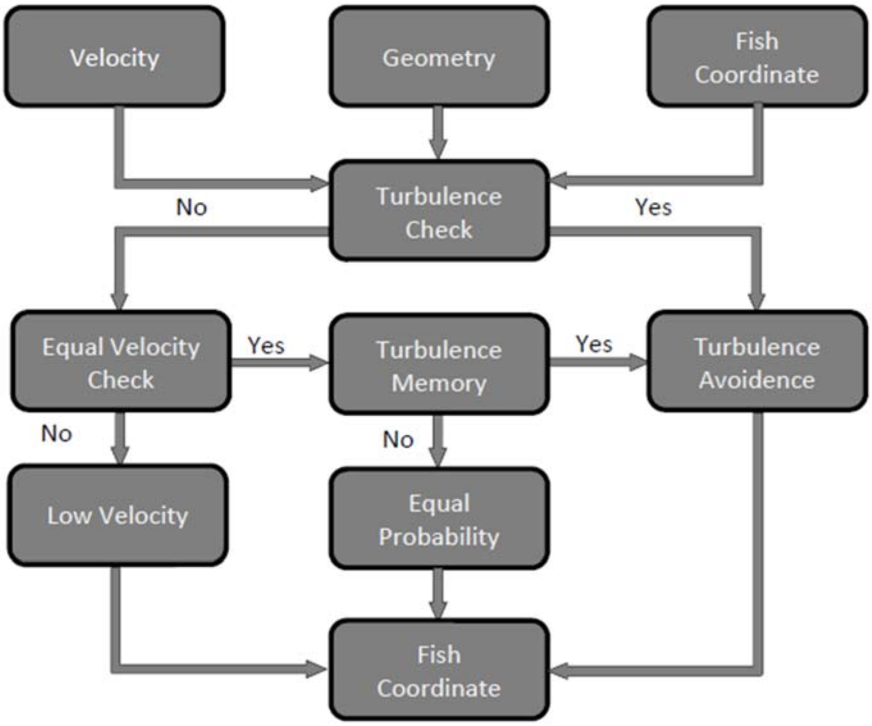


Figure 2.3 - 1: Structure of the model [source: (Abdelaziz, 2013)]

To start the model, the data related to the culvert geometry, the measured or simulated velocity and the coordinates of the fish at the entrance of the culvert are required. Based on these flow data, the model checks whether there is high turbulence or not. In case of high turbulence, the turbulence avoidance model will be applied. Otherwise, the model checks the velocity at the next three points in the upstream direction searching for the lowest velocity. In this case the minimum energy expenditure model with random probability will be applied. In case that the three points have the same velocity, the fish will search in its memory if there was a turbulence in one side within the specific number of previous movements, then the turbulence avoid technique will be applied. Otherwise, the fish will give equal probabilities to the three directions. The steps are repeated until the fish reaches to the most upstream part of the culvert. Finally, the calculated path is smoothed using the moving average filter method.

The energy expenditures are calculated from the smoothed simulated path. It is issued that the fish seeks to minimize energy expenditure by choosing travelling against lower velocities. In the particular model, a fish travelling from downstream will evaluate the velocities in the upstream grid, and select with the lowest velocity, hence the path of minimum energy consumption. This procedure is repeated until ascended the whole structure or if encountered velocity greater than fish burst speed, when the model stops assuming fish returning back with flow direction.

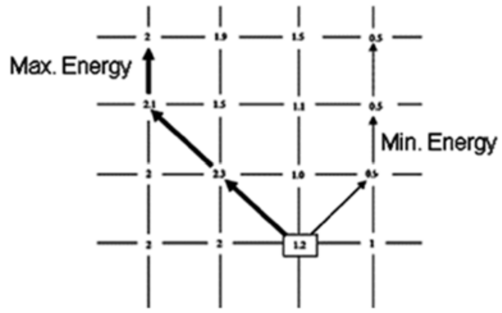


Figure 2.3 - 2: Diagram of decision process for estimating minimum energy expenditure [source: (Abdelaziz, 2013)]

The concept of random movement is quite popular in fish modeling. In this model, it is assumed that the fish moves randomly forward and simultaneously seeks for low velocities. To combine minimum energy concept and random-walk method the following concept was adopted, based on observations:

1. The velocities in the nearby grid cells, namely upstream U_p, upstream left U_l, and upstream right U_r were compared with each other. The path with the lowest velocity takes higher probability P_1, while the middle velocity has the probability P_2 and the highest velocity takes probability P_3
2. The values P_1, P_2 and P_3 are model parameters. They are selected in a way that the sum of them equals to 1.0; P_1 is greater than P_2 and P_2 is greater than P_3. These values are problem-dependent and must in general be adjusted to the flow domain and the fish the observed path during the model calibration.
3. A pseudo random value between 0 and 1.0 was calculated using Wichmann-Hill's random number generator (Wichmann & Hill, 1982).
4. If the random value falls between 0 .0 and P_1, the fish will go to the lowest point.
5. If the random value falls between P_1 and P_1+P_2, the middle velocity will be selected. Otherwise, the highest velocity will be selected (Figure 2.3 - 3).

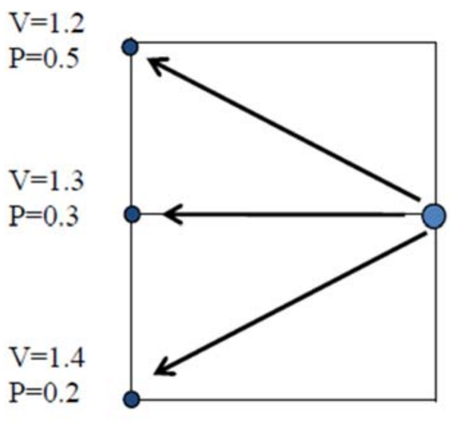


Figure 2.3 - 3: Minimum energy concept with random movement [source: (Abdelaziz, 2013)]

Turbulence is important to fish, since they feel and respond to shear stress and turbulence. A velocity gradient was used as indicator of turbulence, if it exceeds a threshold the fish takes into account the effect of turbulence avoidance. At this point, Sensory Query Distances (SQD) are introduced to relate the length of the fish, to the area in which it detects stimuli.

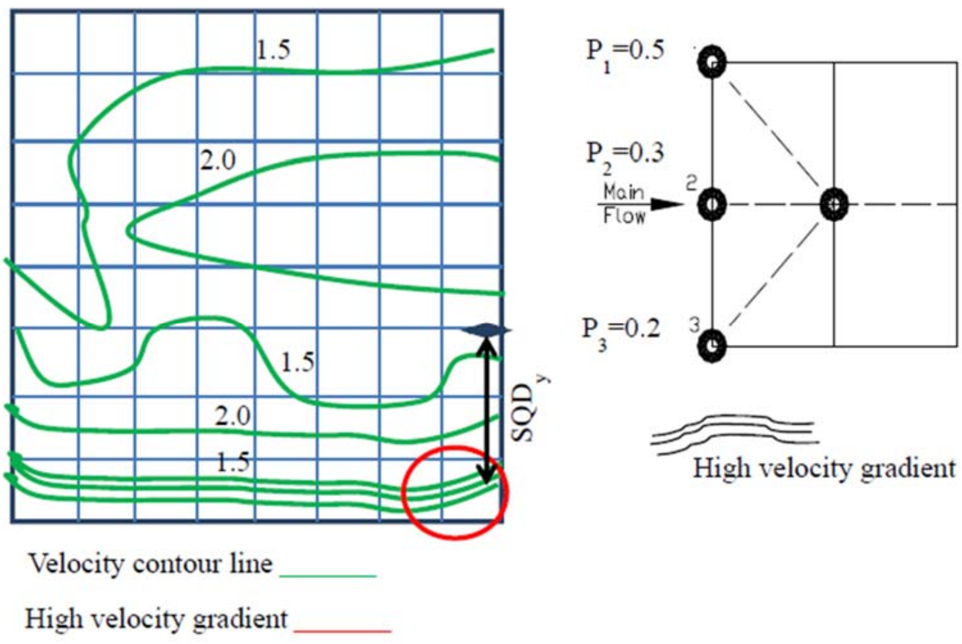


Figure 2.3 - 4: Effect of turbulence on fish movement [source: (Abdelaziz, 2013)]

When the velocity contour lines are perpendicular to the stream direction, the mean flow velocities in the surrounding cells of the fish location are equal (Up=Ul=Ur). In this case, the presence of turbulence effect has a certain role in the selection of the fish path. In this model, it can be estimated as follows:

1. If no turbulence effect is included, the probabilities of the fish to swim upstream, upstream right or upstream left are equal (P1=P2=P3=0.333).
2. When the fish passes a turbulence area, it will try to avoid high turbulence (sensory ovoid). In this case, the fish will select the path according to the lowest velocity gradient.
3. After some movements, the distance between the fish position and the detected turbulence place will be greater than SQDs. Although there is no turbulence flow any more in the domain surrounding the new location, the fish will still prefer to move in the same direction away from the turbulence zone.
4. After a certain time period, the fish will forget totally the turbulence effect and the swim probabilities will be defined as described in the case (1). This forget-time-period will be adjusted with a constant number of movements and can be defined during the model calibration.

To smooth the random effect, which cause results that not abide by observations, the moving average method is used. The algorithm used is the following:

$$\boldsymbol{Y(i)} = \frac{\sum_{K=i-(M-1)/2}^{K-i+(M-1)/2} \boldsymbol{Y(K)}}{\boldsymbol{M}} \qquad (2.3 - 1)$$

Where M is an odd number and at the particular model was taken as 5.0.

The energy fish deliver, if they are to pass through passage structures, is a combination between the energy expenditure inside the structure and the energy expenditure at the entrance and the exit of the structure.

To accumulate energy expenditure through fish movement, the sum of the forces that the fish experiences are interpreted along with their parameters, funneling to the following expressions:

P_f is the power that a fish expends to overcome the drag force and it is a product of the drag force and the velocity of the fish *V_f*.

$$P_f = F_D * V_f \quad (2.3 - 2)$$

Finally, the energy expended throughout a culvert is the following:

$$E_f = \sum_{i=0}^{n} P_f * t_i \quad (2.3 - 3)$$

The time taken for a fish to swim an increment *i* is estimated by the equation:

$$t_i = \frac{\Delta x}{V_f + V_w} \quad (2.3 - 4)$$

Where *Δx* is the increment of the path, *V_w* is the velocity of the flow at the direction of the fish.

The way that a fish enters a culvert form downstream is a subject to many elements, if the height difference exceeds a specific value the fish will jump out of the water to overcome the obstacle. The energy consumed by a fish during leaping combined that of overcoming its own weight is calculated by the following expression:

$$E_{Leaping} = W \frac{\Delta h}{\sin^2 \theta} (1 - \sqrt{0.024})^2 \quad (2.3 - 5)$$

The number of the attempts until the fish pass successfully the obstacle can be calculated on site or by the equation of Kondratieff & Myrick.

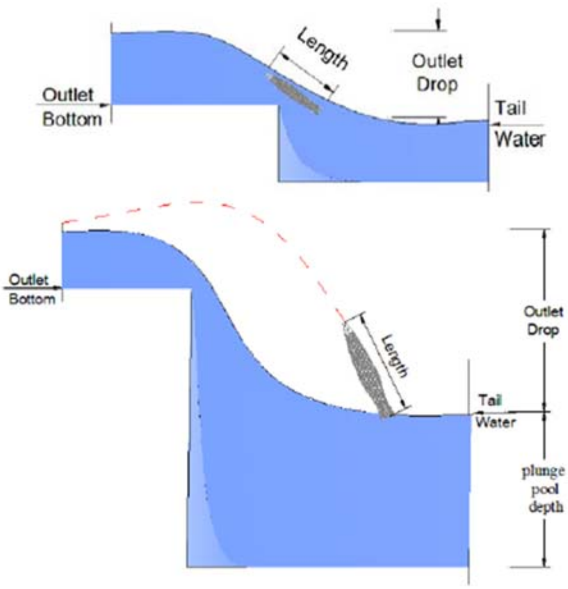


Figure 2.3 - 5: Fish entering the culvert from downstream [source: (Abdelaziz, 2013)]

Computing actual fish energy**,** it is assumed that the initial fish energy can be calculated using the energy expenditure method using Burst speed and fatigue time. The latter, is assumed to vary randomly between two extreme values, which are subject to calibration.

The actual fish energy is calculated as:

$$E_f = 0.02064 * \rho * v^{0.2} * V_f^{2.8} * L_f^{1.91} * [t_{min} + (t_{max} - t_{min}) * rand] \quad (2.3 - 6)$$

where *rand* represent a uniform random value.

It should be mentioned that the depth of the water is limited by a minimum value to prevent fish injury and oxygen starvation.

Finally, a new method to calculate passage's barrierity, which expresses the degree that the culvert is a barrier, that consists of the following steps:

1. The actual fish energy is calculated based on the fish fatigue time and the burst speed. The fish fatigue time is assumed as a random value varies according to the fish exhaustion.
2. The culvert leaping barrierity is determined according to the minimum pool height and the maximum vertical leap distance.
3. The culvert will be considered as fish leap energy barrier if the actual fish energy is less than the required leaping energy.
4. The culvert depth barrierity will be considered if the water depth at any part of the culvert is less than the minimum depth suitable for fish swimming. Additionally, the culvert velocity barrierity is considered when the minimum velocity at any cross-section is more than the burst speed.
5. The remaining fish energy is calculated at each time step and if this energy is less than zero. The culvert will be considered as culvert energy barrier.

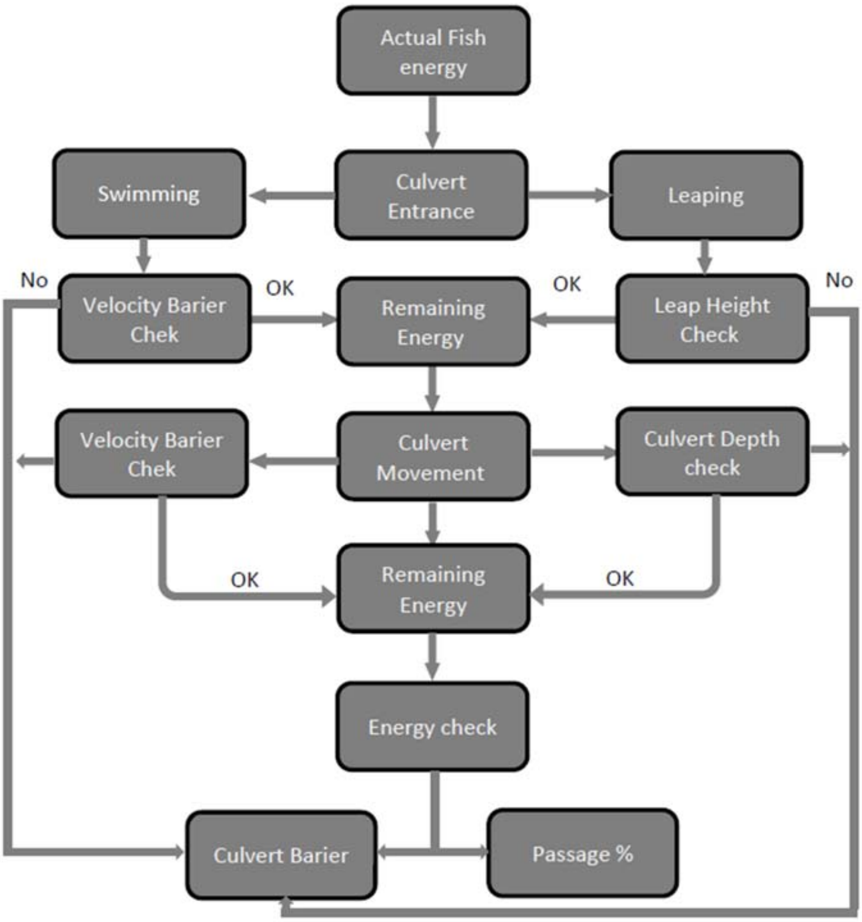


Figure 2.3 - 6: Diagram for culvert barrier method [source: (Abdelaziz, 2013)]

• Model for fish movement in the flow conditions with variable directions

The first model refers to upstream movement of fish when the direction of main flow is uniform. The second model will be presented, where the flow direction changes from point to point. In this model the fish again tries to minimize energy expenditure by choosing lower velocity paths, but simultaneously recognizes the direction of the fish way based on high water flow.

Combining this idea with the previous model, the following modification to the previous model can be suggested. Figure 2.3 - 7 shows the flowchart of the proposed model. According to this flowchart, the main steps of the model can be summarized as follow:

1. To start the model, the data related to the culvert geometry, the measured or simulated velocity and the coordinates of the fish at the entrance of the culvert are required.
2. Based on these data, the model checks whether there is an opening within a distance around the fish in the upstream direction or not.
3. In case of the presence of the opening, the fish will go directly toward the opening.
4. Otherwise, the model checks the maximum velocity within a distance around the fish in the upstream direction.
5. If the maximum velocity around the fish is less than a special value which can be determined during model calibrations (e.g. a half of the fish length/s), the fish could not recognize the flow direction and the random movement will be selected.
6. On the other hand, if the velocity is high enough for the fish to recognize the upstream direction, the fish will go in a direction against the direction of the high flow.
7. In this case, the direction conversion will be done to allow the low energy and 60 turbulent model to be applied.
8. The steps mentioned above are repeated until the fish reaches to the most upstream part of the culvert.
9. Finally, the path is smoothed using the moving average filter method.
10. The energy expenditures are calculated from the smoothed simulated path.

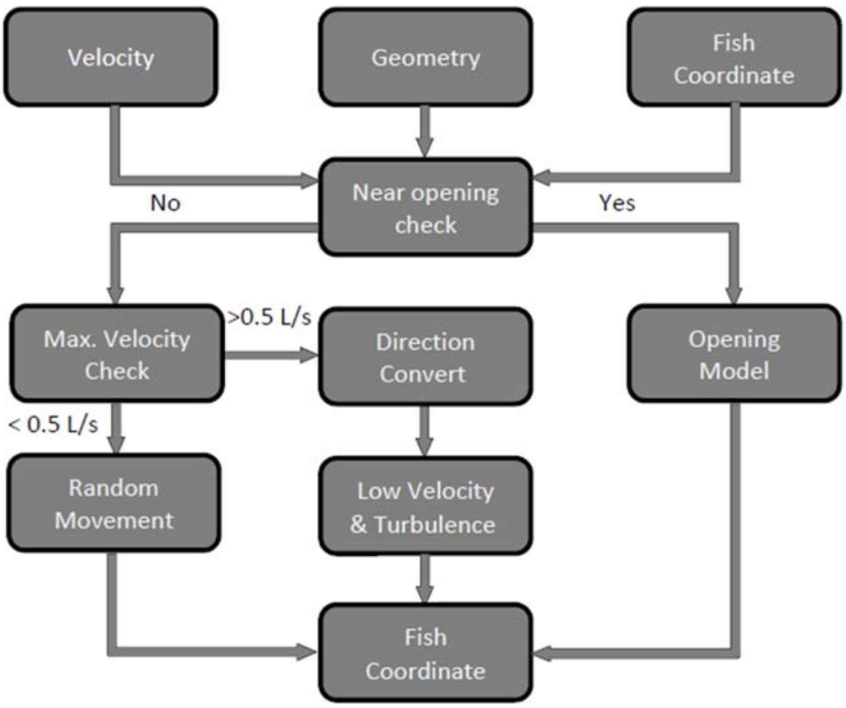


Figure 2.3 - 7: Structure of the two dimensions' model [source: (Abdelaziz, 2013)]

The near opening check is related with the decision-making information and represented as a sensory ovoid. The fish tries to locate if the is any opening within the distinctive distances SQDx and SQDy and if so directs toward opening, unless the water velocity exceeds fish burst speed.

As mentioned fish examines the velocity within the distinctive distances, however if the maximum velocity located close to the fish is lower than a specific value, the model assumes that the is unable to recognize the flow direction, so it chooses randomly one 8 points of direction surrounding. In the contrary, if the maximum velocity is higher than this specific value, the fish will choose the maximum velocity direction. Based on the flow direction, the fish will select the direction of the next movement. Four cases can happen as indicated in Figure 2.3 - 8:

1. If the angle is signed between -45^0 to 45^0, the fish will move horizontally in the direction of –X.
2. If the angle is signed between 45^0 to 135^0, the fish will move vertically in the direction of –Y.
3. If the angle is signed between 135^0 to 225^0, the fish will move horizontally in the direction of X.
4. If the angle is signed between 225^0 to 315^0, the fish will move vertically in the direction of Y.

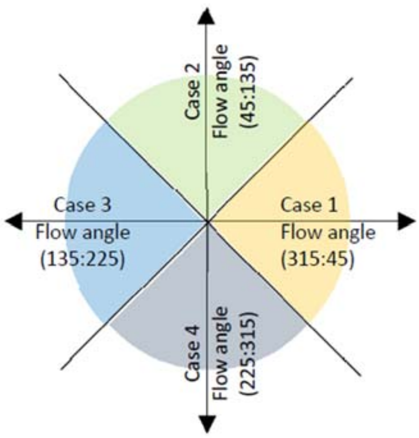


Figure 2.3 - 8: Maximum velocity direction [source: (Abdelaziz, 2013)]

To continue, the fish selects the domain where it can move against by the difference in angle of the direction of maximum velocity and the velocity at the certain point, which should be lower than a specific value, subject to calibration.

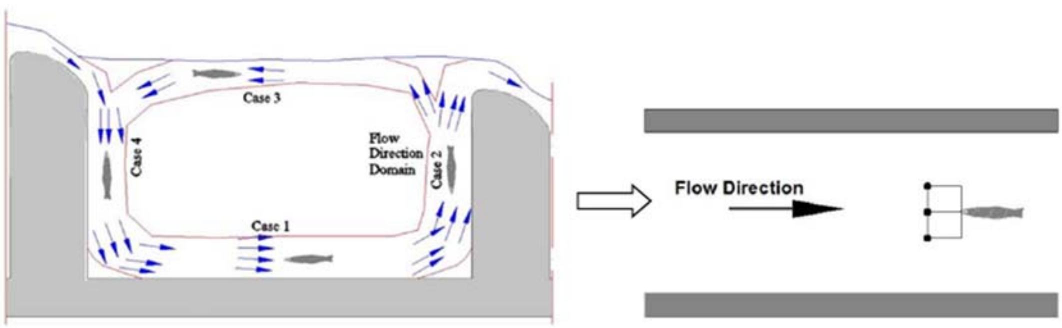


Figure 2.3 - 9: Flow direction domain and conversion to the low energy and turbulent model [source: (Abdelaziz, 2013)]

Inside the domain the fish moves abiding by the concepts of low energy concept with random movement and turbulence avoidance model, as mentioned before. In this point, it should be mentioned that before applying this model a coordinate conversion is applied to convert current to local coordinates.

The velocities in three dimensions are initially examined, if one those cannot be neglected the model will run in two steps. Firstly, the fish movement is calculated in the main level, of the highest two values, and then the fish will follow the direction of the highest flow in a domain in the third direction.

2.4 The model of Goodwin et al (2006)

Goodwin et al (2006) developed an individual-based model (IBM), to understand and forecast fish's movement patterns in accordance with abiotic stimuli. The model introduced is called Numerical Fish Surrogate and it is currently used by the U.S. Army Corps of Engineers and public districts in the design of bypass structures. It consists of a Eulerian framework to govern the physical, hydrodynamic, and water quality domains, a Lagrangian framework to govern the sensory perception and movement trajectories of individual fish, and an agent framework to govern the behavior decisions of individuals.

More specifically, the movement process is decomposed into two steps: firstly, the fish detects and evaluates stimuli and secondly it responds to the stimuli by moving. To represent the range in which the fish acquires decision-making information a symmetrical sensory ovoid is used, although it can be either symmetrical or distorted. The Sensory Query Distances (SQD) draw the sensory ovoid, which actually represents the sensory range of the lateral line, and are composed of two metrics: biological and CFD. Biological SQD_b is related to model time increment Δt (s), fish body length S_f (m), and operating range of the fish sensory system to the agent in a 1.0-s time increment D_a (body lengths) calculated as:

$$\boldsymbol{SQD_b = \Delta t * S_f * D_a} \qquad (2.4 - 1)$$

SQD_{CFD} requires greater distance to acquire information needed, and may alter as the virtual fish moves on the Eulerian mesh, due to different densities of the grid. Finally, the SQD is selected as:

$$\boldsymbol{SQD = max\{SQD_b, SQD_{CFD}\}} \qquad (2.4 - 2)$$

In addition, SQD may be subject of modifications to include factors as: fish physiological condition, time of day, water quality, and whether the fish swims alone or is part of a school. User-defined proportions cause fluctuations to capture environmental gradients at more than one spatial scales.

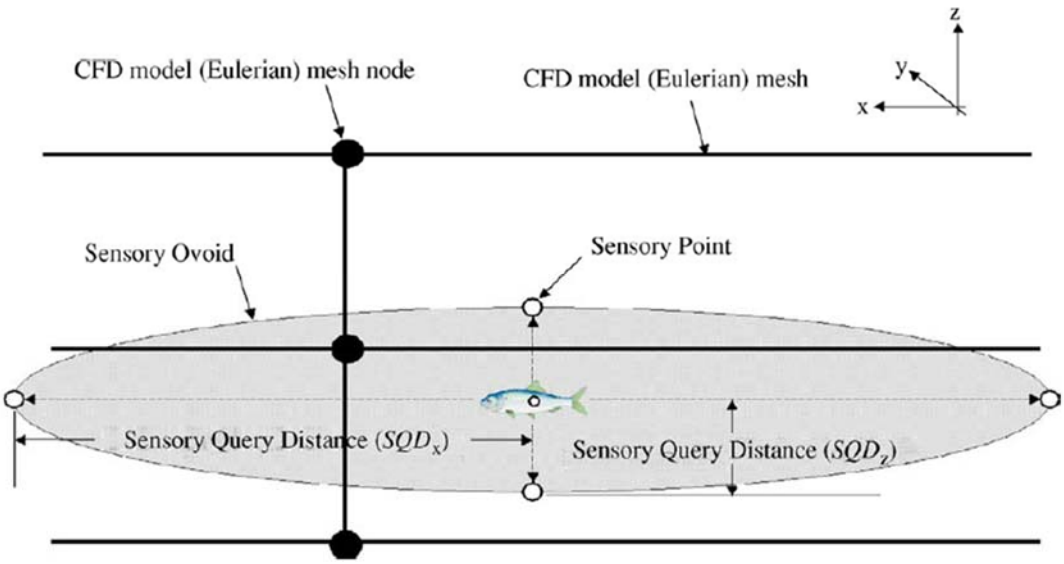


Figure 2.4 - 1: Two-dimensional view of a fish sensory ovoid [source: (Goodwin, et al., 2006)]

Behavior rules in the model produce a 3-D volitional swimming vector in which speed and orientation are determined interdependently for each fish at every 2.0-s increment and the outcome is analyzed into Cartesian vector components (u_f, v_f, w_f) which are added to the flow vectors (u, v, w) to update fish location as a relation of its previous position.

$$x_t = x_{t-1} + (u + u_f) * \Delta t \quad (2.4 - 3)$$

$$y_t = y_{t-1} + (v + v_f) * \Delta t \quad (2.4 - 4)$$

$$z_t = z_{t-1} + (w + w_f) * \Delta t \quad (2.4 - 5)$$

Numerical Fish Surrogate uses a particle-tracking algorithm to deal with difficulties and limitations caused by the simulation of continuous movement in a discretized mesh.

To focus on the sensory process and behavior decisions, a fish perceived to respond only to hydrodynamic stimuli with no visual or tactile contact with solid structures. Although the complexity of the fish's identifying mechanism it is hypothesized that salient hydraulic cues are driving its behaviors by considering hydrogeomorphology, the Navier-Stokes equation of fluid motion and fish sensory capabilities. In free-flowing streams, flow pattern results from friction resistance, from a solid boundary or an obstruction in the flow, provide cues to migrating fish allowing them to navigate through complex flow fields. These hydrodynamic cues considered as environmental agents that interact with the fish agent.

Four agents are used: the default (A_0) occurs in the absence of other agents, wall-bounded flow gradient (A_1), free-shear flow gradient (A_2), and pressure gradient (A_3) – separated by strain threshold values: k_1, k_2 and k_3 respectively. The total strain perceived is calculated as:

$$l(t) = \log_{10}\left[\frac{S(t)}{S_0}\right] \quad (2.4 - 6)$$

The ability of detection threshold excess is in accordance with Weber's Law ("just noticeable difference" between a signal and the background stimuli is a constant fraction of the background stimuli intensity (Goodwin, et al., 2006), which expressed as:

$$\frac{l(t)}{l_a(t)} > k_i \qquad (2.4 - 7)$$

where l_a is the perceived background or acclimated strain level, k_i is the threshold level associated with A_i.

A moving average is used to adjust the level of perceived total hydraulic strain:

$$l_a(t) = (1 - m_{strain}) * l(t) + m_{strain} * l_a(t-1) \qquad (2.4 - 8)$$

where m_{strain} is an adaptation coefficient with a value between 0 and 1 that adjusts how information from the present combines with information from the past.

The algorithm allows a virtual migrant to identify one of the four agents, each of which elicits a specific behavior (Figure 2.4 - 1): (B_0) swimming with the flow vector, (B_1) swimming towards increasing water velocity to minimize strain, (B_2) swimming towards decreasing water velocity or against the flow vector to minimize strain, and (B_3) swimming towards acclimated pressure (depth). Swimming speed is bounded above by approximately 10 and below by 2 body lengths per second. Fish orientation and speed for each time increment are described by the specified behavior B_i plus a random component.

Table 2.4 - 1: Agents, behavior responses and agent coefficients [source: (Goodwin, et al., 2006)]

i	**Agent (*A_i*)**	**Behavior Response (*B_i*)**	u_i	m_i
0	Null	Follow flow	0.35	1.00
1	Wall-bounded flow gradient	Swim towards increasing water velocity	0.55	0.80
2	Free-shear flow gradient	Swim towards decreasing water velocity or against the flow vector	0.99	0.982
3	Pressure gradient	Swim towards acclimated depth	0.99	0.935

The neurological response to the agents described is not easily simulated, since the fish has a great variety of time-varying information to perceive and an adequate number of behaviors to adopt. To overcome this obstacle Goodwin et al used a game-theory framework developed, in which each behavior has an associated intrinsic utility (u_i). The fish estimates the probability (P_i) of obtaining the utility from the information. The acquisition of the latter is treated as a discrete event; hence it may burden bioenergetics cost (C_i). The expected utility (Ui) from the behavior (Bi) is:

$$U_i(t) = P_i * u_i - C_i \qquad (2.4 - 9)$$

The fish updates the probabilities for the different behaviors at each time step and selects the behavior that has the greatest expected utility. The time dependence of the probability with the previous interval is expressed as:

$$P_i(t) = (1 - m_i) * e_i(t) + m_i * P_i(t-1) \qquad (2.4 - 10)$$

where $e_i(t)$ is a Boolean measure of the agent information in the time interval and m_i is a memory coefficient weighting the current information and the past probability P_i (t−1). If the fish detects an agent the Boolean measure is 1 or otherwise 0. Coupling this with the equation (2.4 – 7) we get the following definition of events:

$$P_i(t) = \begin{cases} 0, if \ \frac{l(t)}{l_a} < k_i \\ 1, if \ \frac{l(t)}{l_a(t)} \geq k_i \end{cases} \quad (2.4 - 11)$$

The construct for the Numerical Fish Surrogate is illustrated in Figure 2.4 - 2. Bioenergetic cost is not included in the present formulation.

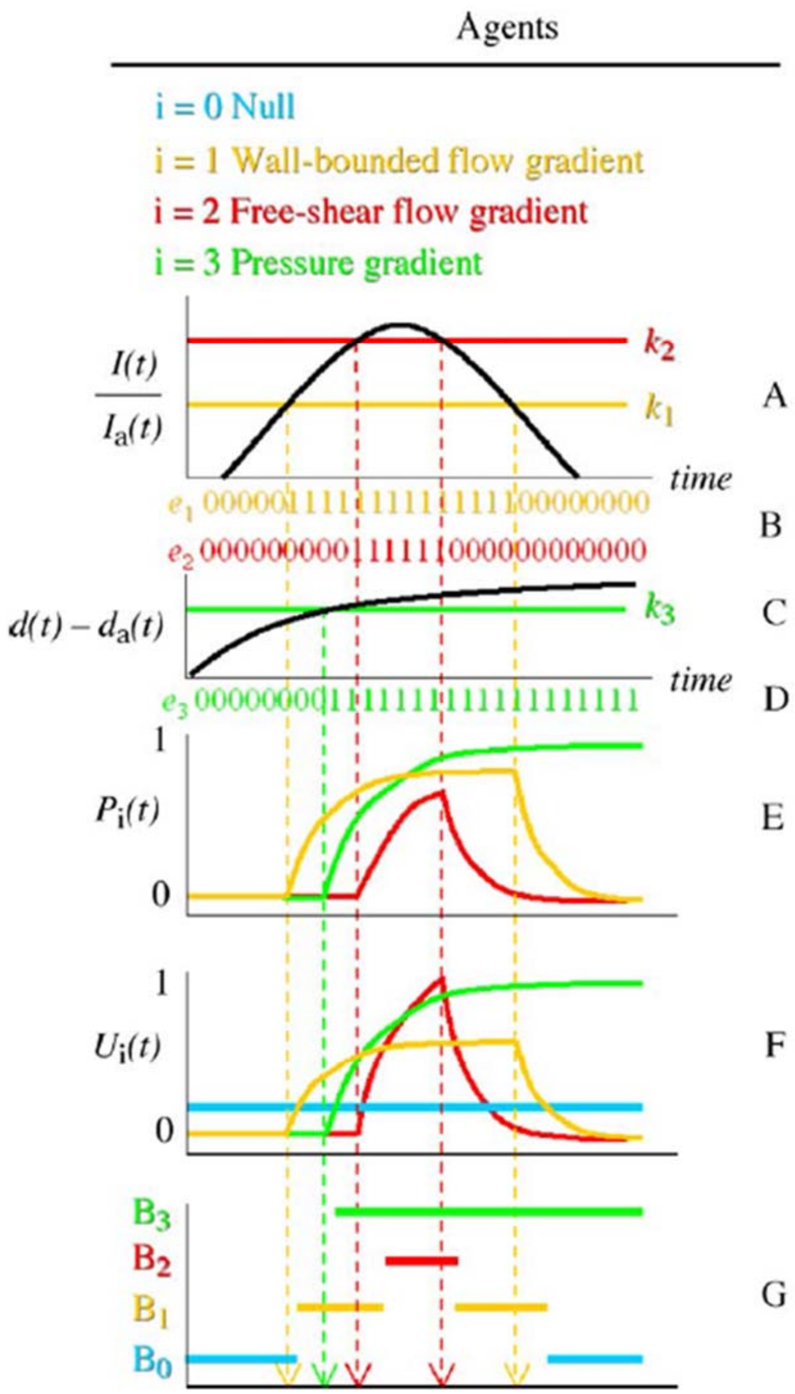


Figure 2.4 - 2: Illustration of the agent-based, event-driven algorithm for migrants switching between behaviors B0, B1, B2, and B3 [source: (Goodwin, et al., 2006)]

2.5 The model of Haefner and Bowen (2002)

Haefner and Bowen (2002) developed a physical-based model of fish movement in fish extraction facilities to contribute to improve planning of a new Tracy Fish Collection Facility (TFCF), which is part of Tracy Pumping Plant (TPP) in San Francisco, California. The primary goal of TFCF is to isolate fishes, through a system of two sets of vertical louvers, into holding tanks, that therefore are transported back to the San Francisco Bay-Delta.

The basic concept of the model perceives the fish as a single body (two-dimensional inflexible) moving in a fluid according to Newtonian forces present in the medium, that also uses the basic surviving instinct of obstacle avoidance. For implication as well as simplification reasons a 2D approximation is implemented. Accelerations of the fish attract significant level of interest, since they are affected by both fluid velocities and fish's behavior. Water velocities provide the physical forces acting on a fish, however, the behavior, physiology, and, especially, the size of the fish determine its reaction to obstacles.

Allometric parameters are essential to compute the forces acting on fish or produced by it. (Allometry is the change in organisms in relation to proportional changes in body size. source: http://www.britannica.com/science/allometry)

Table 2.5 - 1: Allometric parameter definitions, nominal values and units [source: (Haefner & Bowen, 2002)]

Symbol	Definition	Nominal value
S_c	Wetted surface area coefficient	0.465 (m)
S_e	Wetted surface area exponent	2.11 (unitless)
m_c	Mass coefficient	16.15 (kg)
m_e	Mass exponent	3.14 (log(kg)/log(m))
B_c	Burst duration coefficient	0.164 (s)
B_e	Burst duration exponent	0.358 (log(s)/log(m))

The wetted surface area of a salmonid is related to body length (L) as:

$$S_a = S_c * L^{S_e} \quad (2.5 - 1)$$

In addition, mass is:

$$m = m_c * L^{m_e} \quad (2.5 - 2)$$

To incorporate water mass moved during a thrust an increase of 20% is added to the fish's nominal mass. So the virtual mass is:

$$m_v = m + m_a = 1.2\, m \quad (2.5 - 3)$$

It is stated that five major forces act on a swimming fish: friction and profile drag, pressure drag, interference drag, lift, and induced drag. In the specific model, only friction and profile drag are included whether the rest are neglected. Pressure drag, the drag induced by turbulent flow behind a swimming fish, is neglected on the assumption that the fish movement does not alter the water velocity. Interference drag, the drag produced by fins, is incorporated into the friction drag. Lift is the produced force by the difference between the velocities on each side of the fish and it is neglected due to its very low values. Induced drag, the drag associated with the transport of momentum of the fluid in the opposite direction to the lift of the fish, so it is also neglected.

Friction drag is the force that pulls a non-swimming particle with the flow as a result of the friction between water and the surface of the particle. It is defined here for fish that are aligned towards the flow of the water:

$$D = 0.5 * \rho * U^2 * S_a * C_f \tag{2.5 - 4}$$

w where $U=u_w-u_f$ (water velocity minus fish velocity) in the x and y directions; other variables are defined in Table 2.5 - 2.

Profile drag is the drag produced by a particle oriented towards the flow at angle α. It is incorporated into total drag as a coefficient added to the friction drag coefficient (C_f). The profile drag coefficient (C_p) is approximated as:

$$C_p = min \begin{cases} C_{px} \\ \begin{cases} C_{ps} * (a - C_{ps})^2, if\ a > C_{pf} \\ 0,\ if\ a \leq C_{pf} \end{cases} \end{cases} \tag{2.5 - 5}$$

where C_{ps}=3.0776, C_{pf}=0.1227 and maximum profile drag coefficient (C_{px}) for an ellipsoid oriented into the flow is about 0.3 at Reynolds number 105. This value increases to about 0.6, when the ellipsoid is perpendicular to the flow.

Table 2.5 - 2: Variables and parameters [source: (Haefner & Bowen, 2002)]

Symbol	Definition	Nominal value
A_B	Burst mode acceleration	30.0 (m/s^2)
A_R	Reversing mode acceleration	30.0 (m/s^2)
α	Fish orientation angle to flow	Computed (radians)
B_d	Duration of burst swimming after danger	Allometric (s)
C_f	Friction drag coefficient	0.01 (unitless)
C_p	Profile drag coefficient	Computed (unitless)
C_{pf}	Drag coefficient angular shift	0.1227 (unitless)
C_{ps}	Drag coefficient scale	3.0776 (unitless)
C_{px}	Maximum drag coefficient	0.3 (unitless)
D	Drag force	Computed (newtons)
F	Fraction of burst swimming time lost in burst	1.0 (s)
L	Length of fish	0.05 (var) (m)
M	Swim mode: burst, prolonged, sustained, reversing	Computed (unitless)
m	Mass of fish	Allometric (kg)
m_a	Fraction added mass of fish	0.2 (unitless)
m_v	Virtual mass of fish	$m+m_a$
O	Time remaining for burst mode swimming	Computed (s)
O_{max}	Maximum time for Burst mode swimming	6 (s)
P	Thrust	Computed (newtons)
P	Density of water	1000 (kg/m^3)
S_a	Wetted surface area of fish	computed (m^2)
S_b	Species burst swimming strength	1.0 (var) (uniteless)
S_p	Species prolonged swimming strength	1.0 (var) (uniteless)
S_s	Species sustained swimming speed	2 (var) (L/s)
U	Relative water velocity in x, y direction	Computed (m/s)
U_l	Relative water velocity in x, y direction left of fish	Computed (m/s)
U_r	Relative water velocity in x, y direction right of fish	Computed (m/s)

Symbol	Definition	Nominal value
U_f	Fish velocity in x and y direction right of fish	Computed (m/s)
U_w	Water velocity in x and y direction right of fish	Computed (m/s)
W_b	Fraction of L to use burst swimming	0.5 (uniteless)
W_p	Fraction of L to use prolonged swimming	1.0 (uniteless)

2.6 Choice of the most appropriate model

After analyzed the contemporary models we selected the most suitable one to facilitate the purposes of this study. The model of Haefner and Bowen (2002) relates forces exerted to the fish with its swimming behavior via physical characteristics of fish (length and mass), but does not includes the fish's perception regarding the environmental stimuli. Continuously, the model of Abdelaziz (2013) coupled hydraulic data with the concept of minimum energy expenditure, a discrete random-walk method and other special fish behaviors, however simulated fishes do not have time-varying attributes (other than location) which affect their simulated behavioral responses. Additionally, the model is bounded in roughened channels and pool-type channels.

Conclusively, the model of Goodwin et al (2014) selected as the most appropriate for this study, since it takes into account fish perception of environmental stimuli and composes their movement as a response to those cues, along with a biased correlated random-walk. Moreover, the latter model has the ability to capture fish attributes observed in real fishes, such as that a fish may reject a route several times before entering, and some fish never return to a route after the first encounter.

Table 2.6 - 1: Comparison between the models

	Haefner and Bowen	Abdelaziz	Goodwin et al
Applications	Fish collection or diversion facilities	No	Bypass structures by U.S. Army Corps of Engineers and public utility districts in USA
Hydrodynamic modelling	No – Input from CFD	No – Input from CFD	No – Input from CFD
Individual-Based-Model	Yes	Yes	Yes
Main output	Passage results of the facilities	Fish trajectory	Fish trajectory and Passage results
Dimensions	2D	3D	3D
Swimming behaviors	3	2	4
Choice of swimming behavior	Set of simple decision rules	Different fish passage types, for roughened and pool-type channels	Expected utility theory
Upstream migration	No	Yes	Yes
Downstream migration	Yes	Yes	Yes
Video image processing	No	Yes	No
Forces exerted to the fish	Yes	No	No
Obstacle avoidance	Yes	No	Yes
Turbulence avoidance	No	Yes	Yes

	Haefner and Bowen	**Abdelaziz**	**Goodwin et al**
Energy expenditure	Yes	Yes	No
Random-walk method	No	Yes	Yes
Time-varying attributes	No	No	Yes
Perception of environmental stimuli	No	No	Yes
Acclimatization	No	No	Yes
Verification through observed data	Yes	Yes	Yes
Citations[1]	28	2	112
Available source code	No	No	Yes[2]

[1] source: Google Scholar
[2] After communication with Dr. Goodwin

3 PRESENTATION OF THE ELAM MODEL

3.1 Decoding DRIVER

In this section the role of any subroutine involved in the program is illustrated. To be more precise we decompose and analyze all the subroutines, following the DRIVER's structure, in order to get familiar and understand any aspect of this highly complex program.

A scribble flowchart (see 3.2) for DRIVER subroutine is conducted, to facilitate decoding process. Due to complexity and great amount of procedures composing the subroutine the scribble format was selected. As mentioned before, information concerning each subroutine are presented below in this section, while numbers in parenthesis are in correlation with those appeared on the flowchart. By "Other Processes" is denoted a whole section of a program which serves one or more purposes, otherwise the name of specific subroutine is used. Subroutines marked with a (*) are not presented individually in the flowchart, but are called by other sections of the program and presented as encountered.

It should be highlighted that the following analysis emphasized on environmental field procedures and not on every aspect of the program, since that was our primary goal.

Other Processes (1)

To begin with the program sets the time step for which time-based fish data will be stored (i.e. last=1 or present=2 time step, in our case present time step is selected)

INIT_ZONE_GEOMETRY (2)

This subroutine extracts from connect.asc file:

- the number and the dimensions of the zones,
- connectivity between each mesh zone.

All cell faces that lie at an internal boundary within the mesh (i.e., do not represent the exterior system or some internal impermeable boundary) are associated with a cell in the adjacent, neighboring zone. The relationship is based on the neighboring cell having the largest shared surface area. For all cells at the boundary of a zone, four array values must be specified (Table 3.1 - 1):

- solid wall boundaries → all 4 array values set to `0`
- water surface (treated as a solid wall boundary) → all 4 array values set to `0`
- true outflow boundaries → all 4 array values set to `-5`
- true inflow boundaries → all 4 array values set to `-4`

Table 3.1 - 1: Zone connectivity arrays

Arrays for cell interfaces when `I=1`	
`I1X(J,K)`	I-index of the cell in adjacent zone where the fish should be sent
`I1Y(J,K)`	J-index of the cell in adjacent zone where the fish should be sent
`I1Z(J,K)`	K-index of the cell in adjacent zone where the fish should be sent
`N1X(J,K)`	Zone of the cell in adjacent zone where the fish should be sent
`NMX(J,K)`	Zone of the cell in adjacent zone where the fish should be sent

Arrays for cell interfaces when I=Imax	
IMX(J,K)	I-index of the cell in adjacent zone where the fish should be sent
IMY(J,K)	J-index of the cell in adjacent zone where the fish should be sent
IMZ(J,K)	K-index of the cell in adjacent zone where the fish should be sent
IMX(J,K)	I-index of the cell in adjacent zone where the fish should be sent
Arrays for cell interfaces when J=1	
J1X(I,K)	I-index of the cell in adjacent zone where the fish should be sent
J1Y(I,K)	J-index of the cell in adjacent zone where the fish should be sent
J1Z(I,K)	K-index of the cell in adjacent zone where the fish should be sent
N1Y(I,K)	Zone of the cell in adjacent zone where the fish should be sent
Arrays for cell interfaces when J=Jmax	
JMX(I,K)	I-index of the cell in adjacent zone where the fish should be sent
JMY(I,K)	J-index of the cell in adjacent zone where the fish should be sent
JMZ(I,K)	K-index of the cell in adjacent zone where the fish should be sent
NMY(I,K)	Zone of the cell in adjacent zone where the fish should be sent
Arrays for cell interfaces when K=1	
K1X(I,J)	I-index of the cell in adjacent zone where the fish should be sent
K1Y(I,J)	J-index of the cell in adjacent zone where the fish should be sent
K1Z(I,J)	K-index of the cell in adjacent zone where the fish should be sent
N1Z(I,J)	Zone of the cell in adjacent zone where the fish should be sent
Arrays for cell interfaces when K=Kmax	
KMX(I,J)	I-index of the cell in adjacent zone where the fish should be sent
KMY(I,J)	J-index of the cell in adjacent zone where the fish should be sent
KMZ(I,J)	K-index of the cell in adjacent zone where the fish should be sent
NMZ(I,J)	Zone of the cell in adjacent zone where the fish should be sent

INPUTVALUES (3)

This subroutine creates the environment where the user interfaces (Figure 3.1 - 1). It prompts the user for input information and collects the user-defined data regarding simulation settings, more specifically:

- Turn on/off the fish behavior contribution (volitional fish swimming) to particle movement:
  - 1 => behavior rules ON
  - 0 => behavior rules OFF
- Length of time step (seconds) for updating particle positions
- Total number of time steps the particles are simulated
- Number of time steps between consecutive output to files
- Type of files to output:
  - 0 => output only simulation passage files
  - 1 => output simulation passage and fish trajectory files
  - 2 => output all files plus the debug file
- How to store data during simulation. Note: this input is ignored; parameter set to 0.
- Total number of releases (independent simulations) that will be run serially (one after the other) and, then, concatenated into a single result. It is sometimes faster to run 500 fish in separate simulations, one release/simulation after the other (serially) ten times, than to run 5,000 fish in a single simulation. Since fish do not interact this does not appreciably change the results other than impacts that are due to fish getting different random numbers.
- Of the total number of releases (independent simulations) that will be run serially, this indicates which release/simulation # is to be run now.

- This release of fish into the simulation represents the following diel characteristic:
  - 1 => composite (day & night) distribution
  - 2 => daytime distribution
  - 3 => nighttime distribution
- Random number seed (0 < seed < 1000).

Additionally, after user defines all simulations settings needed, the program creates, opens and formats headers for files to output simulated data (v_TecTrack_ZonesAreTime.dat, v_TecPassageResults.dat and v_TecAgentBehaviors.dat).

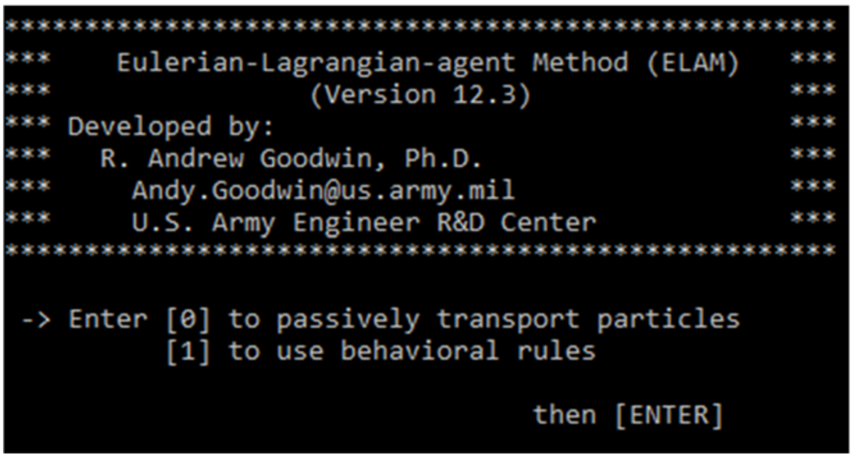


Figure 3.1 - 1: Program's initial display

ReadAgentBehaviorCoeff (4)

This subroutine extracts from AgentBehaviorCoefficients.inp file, sensory and behavior coefficients (i.e. minimum sensory point distance, percent sensory point system, memory coefficient for behaviors, intrinsic utility for behaviors, etc.).

The latter is the only file modified by an optimization routine. Coefficients are fitted in association to data available at each site. The ELAM model can be run simultaneously on multiple hydraulic data sets using scripts. Matlab executes these scripts during optimization, but the scripts and the ELAM model itself can be run independently as well.

Our study does not include optimization routines, thus presented data are defined by the authors regarding juvenile Pacific salmonids in the Columbia/Snake River system.

Other Processes (5)

Between the latter and next subroutine, the DRIVER allocates specific values to some variables. This procedure sets up:

- the number of agents (read by the former subroutine),
- the number of other environmental variables (i.e. pressure) used – if any,
- the use of QUICKSEARCH subroutine, enabling contravariant method, instead of Cartesian-contravariant, to find sensory points (this method is more accurate but a lot slower),
- the space limit as a percent of cell length, beyond cell limits, where the fish is counted as located in the specific cell,
- maximum error allowed between consecutive estimates of the contravariant location,

- maximum number of iterations while trying to converge on the correct contravariant value of location.

READ_ZONE_HYDRO (6)

This subroutine extracts from flow data files (*.hyd) the essential information concerning environmental mesh field variables. Specifically, in this case READ_ZONE_HYDRO subroutine inputs to the main program values regarding water velocity for any of the three directions, total pressure, turbulent kinetic energy, water acceleration and total hydraulic strain for every position in the structured mesh. Total hydraulic strain (3.1 - 1) is a term used by the authors to characterize water flow field, in other words it can be described as the magnitude of the spatial velocity gradient.

$$\boldsymbol{S}(\boldsymbol{t}) = \sum \left|\frac{\partial u_i}{\partial x_j}\right| \qquad (3.1 - 1)$$

It should be highlighted that these data refer to steady-state condition, as well as a DO function forces the program to call consecutively this subroutine for each zone. Additionally, only water flow velocities and acceleration magnitude are participating in the model, the rest feature are for future use.

Other Processes (7)

Between the latter and next subroutine, the DRIVER opens the necessary virtual fish release location files and creates the respective passage files(*.byp). The virtual fish release location files contain the user-defined initial release locations, as well as, the preference for composite, daytime or nighttime release. In the contrary, in the passage files the simulation results are saved. The values in passage files are numbers of fish denoting if they are in the mesh or have abandoned the mesh to either normal or bypass exit.

Then the number of virtual fishes released is identified from the respective file and stored for the rest of the program.

InitializePassageRoutes (8)

This subroutine extracts data regarding available exit routes from the respective file (vExitRoutes.inp) and creates the v_ExitRoutesPassage.pas passage file. Initially the program identifies "special" – by special is denoted a bypass exit route, if any - and outlet exit routes. A fish will be removed if moves into a "special" or outlet exit route. Afterward, if the simulation uses more than one release location files then for the last location file run by this program, passage results from prior runs are loaded in. The input process from exit route file continues with the loading of the number of subzones, composing the "special" and outlet exit routes - if any. Finally, the subroutine identifies the name of the each "special" and outlet exit routes.

ALLOCATEVAR (9)

This subroutine allocates variable arrays related to Contravariant mathematics, Behavior rules and/or Bookkeeping. It also enables fish data storage for all time steps or only for one interval, according to user's decision. Finally, in this subroutine is defined whether agent-to-agent interaction will be activated or not as selected in AgentBehaviorCoefficients.inp file.

Other Processes (10)

In this section the program executes several procedures, such as initialization, set of mesh limits and the beginning of the first time step. At the outset, a great number of essential arrays and variable values are initialized. Then the dimensions of the CFD Model Mesh are determined, where the Contravariant Coordinates of virtual release location will be fragmented. Finally, a search delta (3.1 – 2) is calculated, which denotes the greatest distance from fish to a sensory point.

$$SearchDelta_{i,j,k} = \frac{\frac{\eta}{\log_{10}\left(\frac{A_M}{A_0}\right)} * (1+\delta)}{minSpan} + 5 \qquad (3.1 - 2)$$

where:

- η → a coefficient used to scale minimum sensory point distance according to Acceleration, with a range 0-10. The value is determined in Agent Behavior Coefficients file, and it is equal to 4.5 in our simulations,
- $\log_{10}\left(\frac{A_M}{A_0}\right)$ → is scaled Acceleration magnitude (A_M) as analogous to the decibel scale. A_M is assumed equal to 0.0001 m/sec^2 (minimum value that affects sensory ovoid size) and A_0 is an arbitrary reference equal to 10^{-6},
- δ → is the percent of sensory point distance random increase, ranging from 0.1 to 3. The value is determined in Agent Behavior Coefficients file, and it is equal to 2 in our simulations
- $minSpan$ → is the minimum distance between any I, J, K nodes.

Search delta is the integer part of the value calculated above, while 5 is arbitrary.

After that, the execution of the first time step begins, where fish data are initialized but fish does not move for this time step. For each virtual fish, the fish locations are extracted from the respective file, the program identifies the zone of fish location and calls the SEARCH subroutine (identifies the fish location and convert it into contravariant values) for the respective zone and fish. Subsequently, the location of the fish is evaluated regarding the bounds; if the fish is released in a location out of bounds it is ignored, otherwise the necessary information for fish number and location zone are stored. This procedure is repeated for all the fishes. If all fishes are released at an out-of-bound location, the ENDOFRUNOUTPUT subroutine is called. If the latter is not true, the program prints on the user's display the number of out of bound releases and continues.

SEARCH (11)

This subroutine identifies the fish location and converts it into contravariant values. To begin with, this subroutine determines for each cell the first and the last node, in order to be able to set up every cell and the respective search volume (Figure 3.1 - 2). Then the program identifies and checks the way that values of X, Y and Z are increasing or decreasing with I, J and K indexes. If an inconsistency occurred the subroutine terminates its operation. Afterwards, for each cell, fish's displacement from the cell corner is computed and via average cell metrics (the average position of cell's nodes with its respective adjacent nodes) it is tried to be determined the fish location. For the latter position average metric coefficients are computed and then the calculation of contravariant values of fish location is executed. The error convergence criteria are set and tests are executed to reassure that the contravariant values are reasonable. If there are any miscalculations, new values are reassigned to the previous and the data are stored.

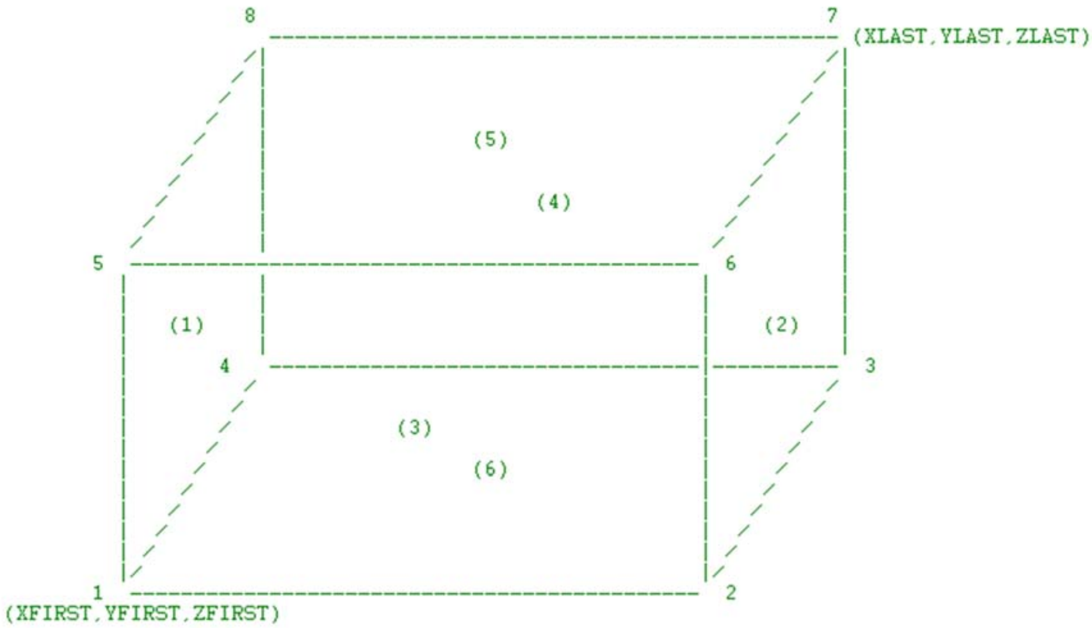


Figure 3.1 - 2: Representation of research volume (schematic illustration in the original code)

ENDOFRUNOUTPUT (12)

This subroutine outputs simulation data to files and screen, as it is the last subroutine executed before program's termination. Initially, the v_readme.out file is outputted, which describes the way that fish data are presented. Then, abiding to user's output preference from simulation settings, v_TecTrack_ZonesAreIndividualFish.dat file is created and written. Several information regarding conversion and violation errors of contravariant values etc. are printed on the user's screen.

Other Processes (13)

In this section the program executes error check to Cartesian-to-contravariant calculations and interpolates mesh-based data. Initially, via PAROUT subroutine contravariant locations converted back to into Cartesian space and the results are outputted in comparison into the Debug file. Then, the HYDROPOINT subroutine is called to interpolate mesh-based data to all sensory points. Finally, variables used in BehaviorRule and SensoryPtCreate are initialized, then if there are "special" exit routes at any zone, fishes last located at this zone are counted. This whole process repeated for every fish.

PAROUT (14)

This subroutine converts back the calculated contravariant location values to Cartesian.

HYDROINTP (15)

This subroutine calculates the respective values of environmental mesh field variables (velocity in x-direction, velocity in y-direction, velocity in z-direction, Pressure, Acceleration magnitude, Total Hydraulic Strain) at fish's sensory points.

At the outset, the program calculates the contravariant values of position for the sensory points. To accomplish that in the best way it uses a search range in accordance to the search delta - bounded by the zone limits – using SEARCH or QUICKSEARCH subroutine. In our case use of QUICKSEARCH is preset, since it enables the contravariant method to find sensory points, otherwise the SEARCH subroutine would be called again to use Cartesian-contravariant method (a more accurate but lot slower procedure).

Afterwards, preparation for interpolation and initialization procedures are executed followed by interpolation of hydraulic information to those sensory points. The 3-D biquadratic interpolation is accomplished via the QINTERPOLCART subroutine, called for every environmental mesh field variable. Finally, interpolation results are checked and stored according to their environmental variable.

QUICKSEARCH (*)

This subroutine is an alteration of the SEARCH subroutine, used for time economy reasons. It also tries to determine - with the exact similar way as in SEARCH subroutine - the contravariant values of fish's location, but it receives as input the contravariant values of the mesh and not the Cartesian to be converted into contravariant. The Cartesian-contravariant method is more accurate but also much slower, so it is preset after the first call of SEARCH subroutine the use of QUICKSEARCH to avoid time consumption.

At this point it should be mentioned that both SEARCH and QUICKSEARCH subroutines, are able to identify the location of every sensory point (see 17) required and not only the center of the fish.

QINTERPOLCART (*)

This subroutine executes the 3-D biquadratic interpolation for each environmental variable. The data points of a three-dimensional grid are interpolated in order to facilitate the simulation calculations of fish movement.

Other Processes (16)

This is the most important section of the program, since all the essential calculations regarding fish movement simulation are executed here. Initially, the total number of active fish (released in-bound) is calculated and the time loop, from 2nd to last time step, starts. Next, the program settles printing processes to v_TecTrack_ZonesAreTime.dat file; ensuring data recorded for the first time step for which fish movement will observed as well as for every time user-defined output interval reached.

Subsequently, for every fish the movement simulation procedure begins. The sensory ovoid is shaped via SensoryPtCreate subroutine, its dimensions are written in the Debug file and stored. Then, sensory points assigned with environmental mesh variables values, result of interpolation and the BehaviorRule subroutine is called. The latter constitutes the essence of whole program, since there, environmental cues evaluated and "translated" to appropriate behavior decisions funneling to moving action. Afterwards, abiding to user preferences fish movement simulation data are outputted (OutputFishData_ZonesAreTime subroutine) and fish locations update (UPDATEFISHLOCATION subroutine).

After fish movement simulation, OutputFishPassageAndDecisions subroutine prints - according to user preferences - fish passage and decision information to respective files followed by procedures regarding fish count and operation of the loop. Finally, DumpDataAndMove subroutine moves fish data in arrays from the present time step to the last, as well as from the next time step to the present.

SensoryPtCreate (17)

This subroutine "shapes" the sensory ovoid of the fish via the 6 sensory rays surrounding the fish (the centroid of the fish is represented by the first ovoid position, so the rest are counted from 2-7). Sensory points are placed in space regarding the fish as follows:

1. The fish itself,
2. (+ X) in the direction the head of the fish is pointing,
3. (- X) in the direction of the fish's tail,
4. (+ Y) to the left of the fish,
5. (- Y) to the right of the fish,
6. (+ Z) in the direction above the fish (parallel to gravity),
7. (- Z) in the direction below the fish (direction of gravity).

As mentioned above regarding sensory ovoid size, the lowest value of acceleration magnitude (A_M) affecting it is equal to 0.0001 m/sec^2. So, the program initially checks the value of acceleration magnitude inputted, to validate that threshold value. All sensory points (2-7), are defined as the displacement from the location of the fish (1), 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 (RAND) - illustrated below.

$$\boldsymbol{SPDIST} = \frac{\boldsymbol{\eta}}{\boldsymbol{Log_{10}}\left(\frac{\boldsymbol{A_M}}{\boldsymbol{A_0}}\right)} \quad (3.1 - 3)$$

$$\boldsymbol{RINC} = \mathbf{1} + \boldsymbol{RRR} * \boldsymbol{\delta} \quad (3.1 - 4)$$

$$\boldsymbol{RAND} = (\mathbf{2} * \boldsymbol{RRR} - \mathbf{1}) * \boldsymbol{C_{40}} \quad (3.1 - 5)$$

where RRR is a random number created by the RandomFromSeed subroutine and C_{40} is the adding range of variability to non-cardinal sensory point locations (extracted from agent coefficient files). The following Table 3.1 - 2 depicts the calculations of the respective locations of sensory points.

Table 3.1 - 2: Sensory points as displacement distances from fish's location

Sensory point #2		
Sensory Ovoid X	=	SPDIST * RINC
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	SPDIST * RAND
Sensory point #3		
Sensory Ovoid X	=	-SPDIST * RINC
Sensory Ovoid Y	=	SPDIST * RAND
Sensory Ovoid Z	=	SPDIST * RAND
Sensory point #4		
Sensory Ovoid X	=	SPDIST * RAND
Sensory Ovoid Y	=	SPDIST * RINC
Sensory Ovoid Z	=	SPDIST * RAND

Sensory point #5
Sensory Ovoid X = SPDIST * RAND
Sensory Ovoid Y = -SPDIST * RINC
Sensory Ovoid Z = SPDIST * RAND
Sensory point #6
Sensory Ovoid X = SPDIST * RAND
Sensory Ovoid Y = SPDIST * RAND
Sensory Ovoid Z = SPDIST * C_{41} * RINC
Sensory point #7
Sensory Ovoid X = SPDIST * RAND
Sensory Ovoid Y = SPDIST * RAND
Sensory Ovoid Z = -SPDIST * C_{41} * RINC

Where C_{41} is the fraction of xy-plane sensory point distance (from fish centroid) to use in vertical direction (SPs 6 & 7).

The program initializes required variables and proceeds to the calculation of the sensory point distances as the difference between the fish location and the respective sensory point location.

RandomFromSeed (*)

This is a subroutine which generates a random number between 0.0 and 1.0 regarding a user-defined input value.

BehaviorRule (18)

This subroutine constitutes the main essence of the whole program, it "produces" the final result of fish movement simulation, regarding all available data. It consists of 6 sections, as presented for better comprehension. At this point it is highlighted that, environmental stimuli can result to 4 possible behavior responses:

- B{1} → swim with flow vector
- B{2} → swim toward faster flow vector
- B{3} → swim against flow vector
- B{4} → swim toward acclimatized depth

Given that, a group of procedures are needed to decide which is the most suitable behavior to apply concerning each time step and fish.

Section 1

At the outset, a variety of variables, essential to the subroutine, are initialized as well as agent parameters and coefficients extract values from AgentBehaviorCoefficients file (Table 3.1 - 3).

Table 3.1 - 3: Agent Behavior Coefficients used in specific subroutine

Memory coefficients (AgtMem)	
for behavior B{1}	1.0 (to maintain constant utility agent)
for behavior B{2}	
for behavior B{3}	Range: 0.0 to 1.0; Probable Range: 0.3 to 0.999
for behavior B{4}	

Intrinsic utilities (AgtIntUtil)	
for behavior B{1}	1.0
for behavior B{2}	Range: 0.0 to 1.0; Probable Range: 0.3 to 0.999
for behavior B{3}	
for behavior B{4}	
Stimulus thresholds (AgtDetctThrshld)	
for behavior B{1}	0.0
for behavior B{2}	Threshold of perceived change in Acceleration
for behavior B{3}	
for behavior B{4}	Threshold of perceived change in Pressure
Memory coefficients for acclimatized values (AgtDetctThrshld)	
for behavior B{1}	0.0
for behavior B{2}	Range: 0.0 to 1.0; Probable Range: 0.95 to 0.999999
for behavior B{3}	0.0
for behavior B{4}	Range: 0.0 to 1.0; Probable Range: 0.95 to 0.999999

Additionally, the length of fish (m), fish's drift velocity (body lengths/sec), fish's cruising velocity (body lengths/sec), fish's sustained velocity (body lengths/sec), fish burst speed (body lengths/sec) and base reference value for calculation of Acceleration in decibel scale are determined (minimum "threshold of detection" of Acceleration in water).

Section 2

Subsequently, the program determines the flow velocity vector relative to swim velocity vector, using VectorRelation subroutine, which outputs the flow velocity vectors for: swimming on xy-plane, swimming on vertical axis and as if fish is stationary. Sensory point locations, along with fish and time step identifications, are printed at debug file. Metrics, regarding velocity and acceleration, are developed from hydraulic data to facilitate the identification of presence of each agent. Then, the calculation of Boolean "events" starts to investigate the presence of an agent (Boolean "events" are values either 0 or 1 that describe whether the agent is present 1 or absent 0). In this program the agents are detected based on:

a) stimulus intensity at its existing location,
b) ambient intensity to which fish is already acclimatized by this time step
c) agent is detected when the difference between (a) and (b) exceeds a threshold value.

So, the following calculations are executed:

◇ Agent Detection Metric (2&3), Acceleration

Perceived change in water acceleration, $E_1(t)$, is based on a *just noticeable difference*:

$$\boldsymbol{E_1(t) = \frac{I_1(t) - I_{\alpha_1}(t)}{I_{\alpha_1}(t)}} \qquad (3.1 - 6)$$

$$\boldsymbol{I_1(t) = \log_{10}\left(\frac{A_M}{A_0}\right)} \qquad (3.1 - 7)$$

$$\boldsymbol{I_{\alpha_1}(t) = \left(1 - m_{a_1}\right) * I_1(t) + m_{a_1} * I_{\alpha_1}(t-1)} \qquad (3.1 - 8)$$

where, $I_1(t)$ is perceived intensity of Acceleration stimulus at the individual's position at time t, $I_{\alpha 1}(t)$ is perceived intensity of Acceleration stimulus to which the individual is acclimatized, m_{a1} is a coefficient within [0,1] scaling how quickly the individual acclimatizes to new intensities of the stimulus, A_M is water acceleration magnitude ($A_M \geq 2*10^{-6}$). Thus, a greater change in perceived intensity of water acceleration is necessary at a greater level of acclimatization to elicit the same response.

In the first execution $I_{\alpha 1}(t)$ receives the value of $I_1(t)$ not smaller than C_{42}, which is the minimum lower-bound for initial acclimatization to Acceleration at start-up, with a probable range: 0.4 ~ 1.0. Afterwards, $I_{\alpha 1}(t)$ is calculated as (3.1-8).

$E_1(t)$ represents the Agent Detection Metric for behaviors {2} and {3}. If Agent Detection Metric is greater than the threshold value, then an event is occurred. Continuously, if Agent Detection Metric is equal or greater than the double of threshold value, the number of events is equal to the integer part of the quotient.

That is also the case regarding behavior {3}, since it detects acceleration changes. However, the threshold value is different from that in B{2}.

◇ Agent Detection Metric (4), Pressure

Acclimatization to swim bladder pressure (depth) is based on the simplifications that perceived changes in swim bladder pressure are proportional to changes in depth and that perceived change does not depend on acclimatized depth. Perceived change in swim bladder pressure (depth) is then:

$$\boldsymbol{E_2(t) = \left|I_2(t) - I_{\alpha_2}(t)\right|} \quad (3.1 - 9)$$

where, $I_2(t)$ is perceived intensity of Pressure stimulus at the individual's position at time t (i.e. the depth), $I_{\alpha 2}(t)$ is perceived intensity of Pressure stimulus to which the individual is acclimatized.

In the first execution $I_{\alpha 2}(t)$ receives the value of fish's depth, while for the rest it is calculated respectively as (3.1-11). The m_{a2} coefficient alters its calculation for this part, as if the fish is swimming upwards:

$$\boldsymbol{m_{a_2} = m_{a_2} * C_{38}} \quad (3.1 - 10)$$

where C_{38} is a memory coefficient for acclimatization fraction when fish swims upward, with a probable range: 0.9 ~ 1.0.

The calculated amount in (3.1-9) is representing the Agent Detection Metric for behavior {4}. If Agent Detection Metric is greater than the threshold value, then an event is occurred. Continuously, if Agent Detection Metric is equal or greater than the double of threshold value, the number of events is equal to the integer part of the quotient.

The results from the previous calculations are printed at Debug file, along with respective essential data.

Afterwards, the program updates the acclimatized values of the previous variables – as presented above. The acclimatization is assumed to follow a common approach in Pavlovian conditioning: the exponentially weighted moving average model:

$$\boldsymbol{I_{\alpha_i}(t) = \left(1 - m_{\alpha_i}\right)I_i(t) + m_{\alpha_i}I_{\alpha_i}(t-1)} \quad (3.1 - 11)$$

where, $I_i(t)$ is perceived intensity of stimulus i at the individual's position at time t, $I_{\alpha i}(t)$ is perceived intensity of stimulus i to which the individual is acclimatized, and m_{ai} is a coefficient within [0,1] scaling how quickly the individual acclimatizes to new intensities of the stimulus.

◇ Probability and Utility

At this point the probability and the utility associated with each agent is calculated, where the agent with the maximum utility value is selected as the one that the fish will respond to. Perceived changes in water acceleration, $E_1(t)$, and swim bladder pressure (depth), $E_2(t)$, that exceed thresholds $k_{B\{j\}}$, j=2,3, and $k_{B\{4\}}$, respectively, support the weight of evidence for the related behaviors B{2,3,4}. The rise and fall in utility occur through Boolean events where $e_B(t)=1$ if perceived change exceeds k_B in a time increment and $e_B(t)=0$ otherwise. Probability, $P_B(t)$, of responding with B{j}, j=2,3,4 increases as:

$$P_B(t) = (1 - m_B)e_B(t) + m_B P_B(t-1) \quad (3.1 - 12)$$

where memory coefficient m_B integrates the amount of past information into the next decision following the notion that intensity or duration of activity in sensory neurons needs to pass a threshold to reach awareness.

The behavior decision is based on an objective function, utility, where each decision in the set of alternatives B{1,2,3,4} has an associated expected utility, U_B (t):

$$U_B(t) = P_B(t)u_B - C_B(t) \quad (3.1 - 13)$$

where u_B is the subjective intrinsic value of behavior B{j} in realizing the goal, i.e., reduction of perceived change in stimulus i=1,2, $E_i(t)$, to back within the threshold tolerance. For simplicity, cost incurred whether or not the goal is realized is set as $C_{B\{1,2,3,4\}} = 0$. Utility of B{1} is fixed over time as $U_{B\{1\}}=0.25$, but utilities of B{2,3,4} fluctuate as the fish transits the flow field. In an increment of time, the behavior B{1,2,3} with highest utility $U_B(t)$ is active. Separately encoded vertical movement B{4} is implemented when $U_{B\{4\}} \geq \beta u_{B\{4\}}$ where β=0.9.

This framework generates behaviors that, on average, maximize utility but, at any given time, may appear to be random.

<u>Section 3</u>

Up to this point in the behavior rule subroutine have accomplished the following tasks:

- developed a metric to identify the presence (intensity) of each agent,
- calculated the value of this metric,
- calculated Boolean events identifying the presence/absence of each agent,
- updated the acclimatized value associated with agents that require,
- calculated the probability and utility associated with each agent.

Using the value of utility, it is decided which behavior to implement and layout the code to implement each behavior. There are two general categories of behavior rules:

1. using a vector as the basis for a behavior response. For instance, behavior could be moving at an angle relative to the direction of flow (e.g. swim with flow vector).
2. using the gradient of a value for a behavior response. For instance, behavior could be moving at an angle relative to the gradient in velocity magnitude, acceleration etc.

Behavior B{1}

The default state B{1} (swim with flow vector) is a correlated random walk biased (BCRW) in the direction of downstream water flow. Initial θ_0 coincides with the flow vector and subsequent B{1} moves occur at a persistent Δθ – with uniform variability within arc $\alpha_{B\{1,2\}}=\pm 20^o$ (xy-plane) and $0.5\alpha_{B\{1,2\}}$ (vertical) – until:

$$R_{[0,1]} \leq e^{(l * C_{\Delta\theta})} - 1 \quad (3.1 - 14)$$

where, $R_{[0,1]}$ is a random number from a uniform distribution [0,1], l=0.005 drives persistence, and $C_{\Delta\theta}$ is the number of consecutive Δθ since θ_0 was restored in line with flow vector. While swim speed is calculated as:

$$S_{B\{1\}} = L_f * \left(S_{cruise} + R_{[-0.5,0.5]} * \left(S_{cruise} - S_{drift}\right)\right) \quad (3.1 - 15)$$

where, L_f is fish length (m), S_{drift} and S_{cruise} are drift and cruise velocities (body lengths/sec), and $R_{[-0.5,0.5]}$ is uniform distribution [-0.5,0.5].

Behavior B{2}
At the state B{2} (swim toward faster flowing water), when B{2} successfully reduces water acceleration A_M in successive time steps, swim speed $S_{B\{2\}}$ is set in the same manner as $S_{B\{1\}}$. However, if B{2} does not reduce water acceleration, then speed boosts as:

$$S_{B\{2,3,4\}} = V_M * (1 + u_b) \quad (3.1 - 16)$$

where, V_M is water velocity magnitude and u_b=1.5 is the boost, with $S_{B\{2,3,4\}}$ bounded as $[S_{cruise}, S_{burst}]$ where S_{burst} is burst velocity (body lengths/sec). Water acceleration is interpolated to each X_t and the V_M gradient, for B{2} orientation is based on sensory acuity of ovoid size uniformly distributed between SQD_{min} and SQD_{max}. To determine SQD margin values the following equations are used:

$$SQD_{min} = \frac{\eta}{\log_{10}\left(\frac{A_M}{A_0}\right)} \quad (3.1 - 17)$$

$$SQD_{max} = SQD_{min} * \left(1 + R_{[0,1]} * \delta\right) \quad (3.1 - 18)$$

where:

- η → a coefficient used to scale minimum sensory point distance according to Acceleration, with a range 0-10. The value is determined in Agent Behavior Coefficients file, and it is equal to 4.5 in our simulations,
- $\log_{10}\left(\frac{A_M}{A_0}\right)$ → is scaled Acceleration magnitude (A_M) as analogous to the decibel scale. A_M is assumed equal to 0.0001 m/sec^2 (minimum value that affects sensory ovoid size) and A_0 is an arbitrary reference equal to 10^{-6},
- $R_{[0,1]}$ → is from uniform distribution [0,1],
- δ → is the percentage of sensory point distance random increase, ranging from 0.1 to 3. The value is determined in Agent Behavior Coefficients file, and it is equal to 2 in our simulations

At this section, concerning B{2} the program, does not execute any calculations, these are conducted in Section 4 where a gradient of a value is used as for behavior response and a vector as in Section 3.

Behavior B{3}
The state B{3} (swim against flow vector), is an escape response that decays relatively slowly with time. The slow dissipation of B{3} utility results in the prolonged B{3} behavior after initiation. Initial θ_0 is the direction opposite of the water flow vector, and subsequent moves occur at a persistent $\Delta\theta$ within arc $\alpha_{B\{3\}}=\pm\varepsilon/\mathrm{Log}_{10}(A_M/A_0)$ (xy-plane) and $0.5\alpha_{B\{3\}}$ (vertical) from the inversed water flow vector, where ε = 180°. With this function, allowed deviation from θ_0 is reduced in high acceleration regions where water flow currents might quickly draw fish into high velocity routes and fast, strongly oriented swimming is required for successful escape maneuvers. Persistent $\Delta\theta$ perpetuates unless θ' exceeds $\alpha_{B\{3\}max}=\pm 90°$ or (3.1-19). Swim speed $S_{B\{3\}}=S_{burst}$ upon transition to B{3} decays in subsequent time steps as:

$$S_{B\{3\}t} = S_{B\{3\}t-1} * (1 - u_d) \qquad (3.1 - 19)$$

where, u_d=0.025, but does not drop below (3.1-16) and it is further bounded as [S_{cruise}, S_{burst}].

Behavior B{4}
The state B{4} overrides the vertical swimming component, if necessary, to ensure θ_{0Z} is toward acclimatized pressure (depth) and uses a persistent $\Delta\theta_Z$ = ±0.1°, but does not override a more favorable θ_{0Z} component in θ_0, and is not less than the inversed vertical flow vector if travel is leading away from acclimatized pressure (depth). Swim speed пreserves a more favorable speed established by B{2,3} or from the prior move and bounded as [S_{cruise}, S_{burst}].

Calculations for B{4} are, also, not executed at this section but in Section 5. However, all four behaviors are presented together in this section for comprehension and simplification reasons.

Section 4
At this section the gradient-tracking agent behavior is calculated B{2}. Conversely, to B{1,3} at B{2} the fish does not move at direction based on a flow vector, but it uses a gradient, and specifically here the velocity gradient. It is attempted to identify the best (minimum) value among the in-bounds sensory points from where the stimulus perceived, calculate xy-plane and vertical swim angles and assign the respective swim speed to the fish.

Section 5
At this section the calculations regarding B{4} are executed. The latter, represents swim toward acclimatized pressure (depth) where the vertical component of xy-plane movement is overridden, if necessary. The swim angle and speed are calculated, and then the speed is checked to be bounded by the respective limits.

Section 6
Up this point the 3 significant variables are determined: a) the swim vector angle relative to the previous swim vector in the horizontal plane, b) the vertical swim vector angle relative to the horizontal, c) fish velocity. In this section, these values are checked, converted to vectors, and finally printed to the debug file.

VectorRelation (*)

This subroutine creates the flow vector velocity (Master Vector) relative to swim vector velocity. The program determines Master Vector's angle relative to xy-plane, vertical angle relative to xy-plane and velocity components as if fish is stationary using hydraulic data inputted.

OutputFishData_ZonesAreTime (19)

This subroutine outputs fish data for each virtual fish to v_TecTrack_ZonesAreTime.dat file.

UPDATEFISHLOCATION (20)

This subroutine updates virtual fish's location from the previous to the present time step. To begin with the subroutine converts fish's velocities and flow velocities to contravariant form, using the TRANSCONTRA subroutine. Then it checks if the fish should be removed from the simulation and proceeds to update the location of the fish evaluating all possible destinations and respective limits.

TRANSCONTRA (*)

This subroutine generates essential data used for conversion of velocities (fish and flow) into contravariant values.

OutputFishPassageAndDecisions (21)

This subroutine tabulates and outputs information regarding passage exits and fish movement decision to the respective files. Initially, it counts the number of virtual fish exiting each passage route, the results are outputted at both v_TecPassageResults.dat and v_TecAgentBehaviors.dat files. Finally, the subroutine summarizes and output fish movement decision information in v_TecAgentBehaviors.dat file.

DumpDataAndMove (22)

This subroutine moves fish data in arrays from the present time step to the last, as well as from the next time step to the present.

DeAllocateMeshData (23)

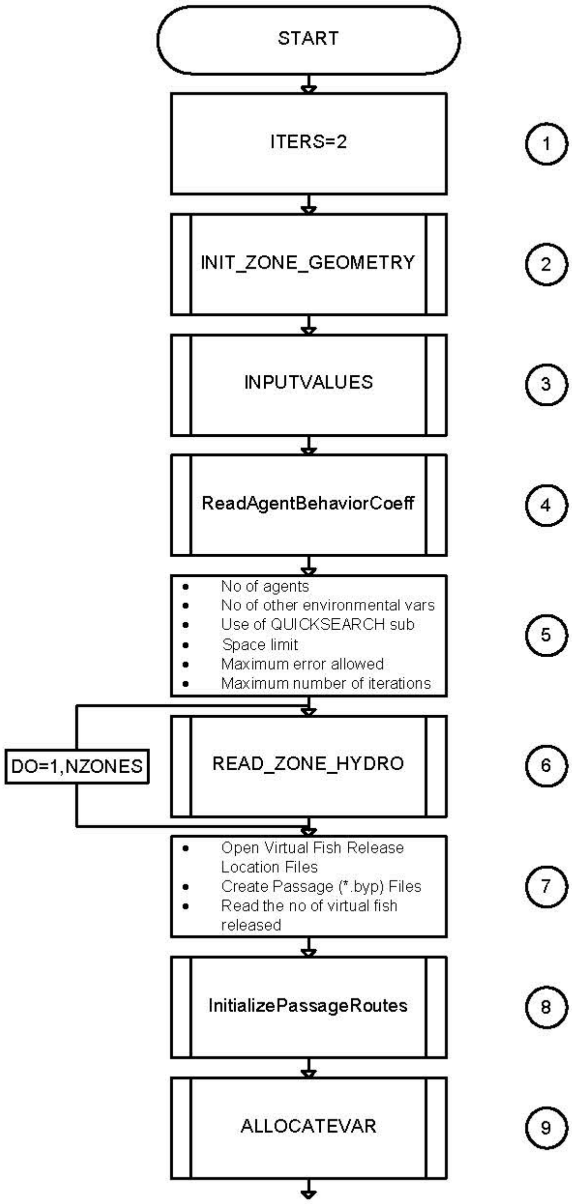
This subroutine deallocates the arrays from all variables used.

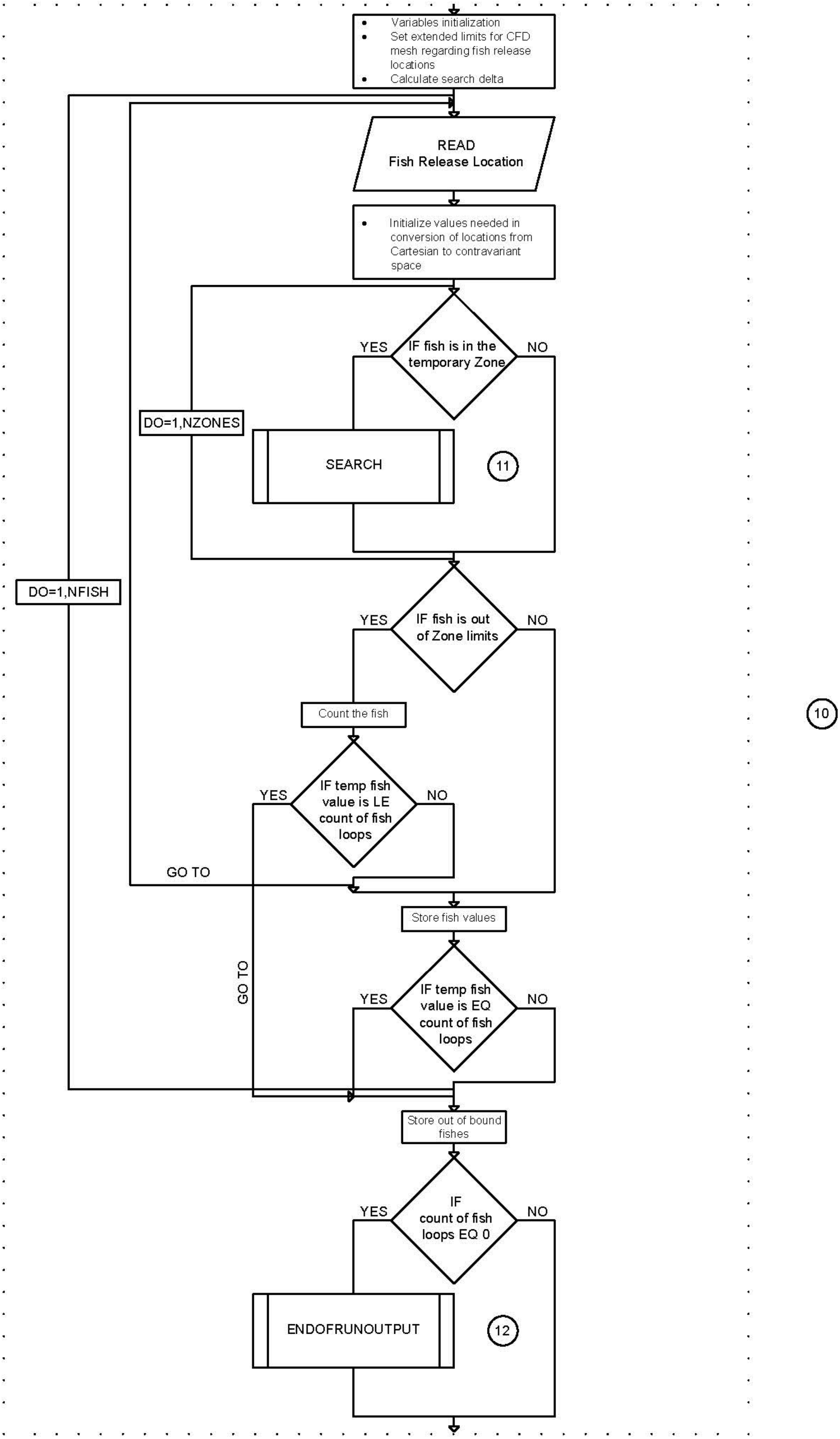
3.2 Scribble flowchart

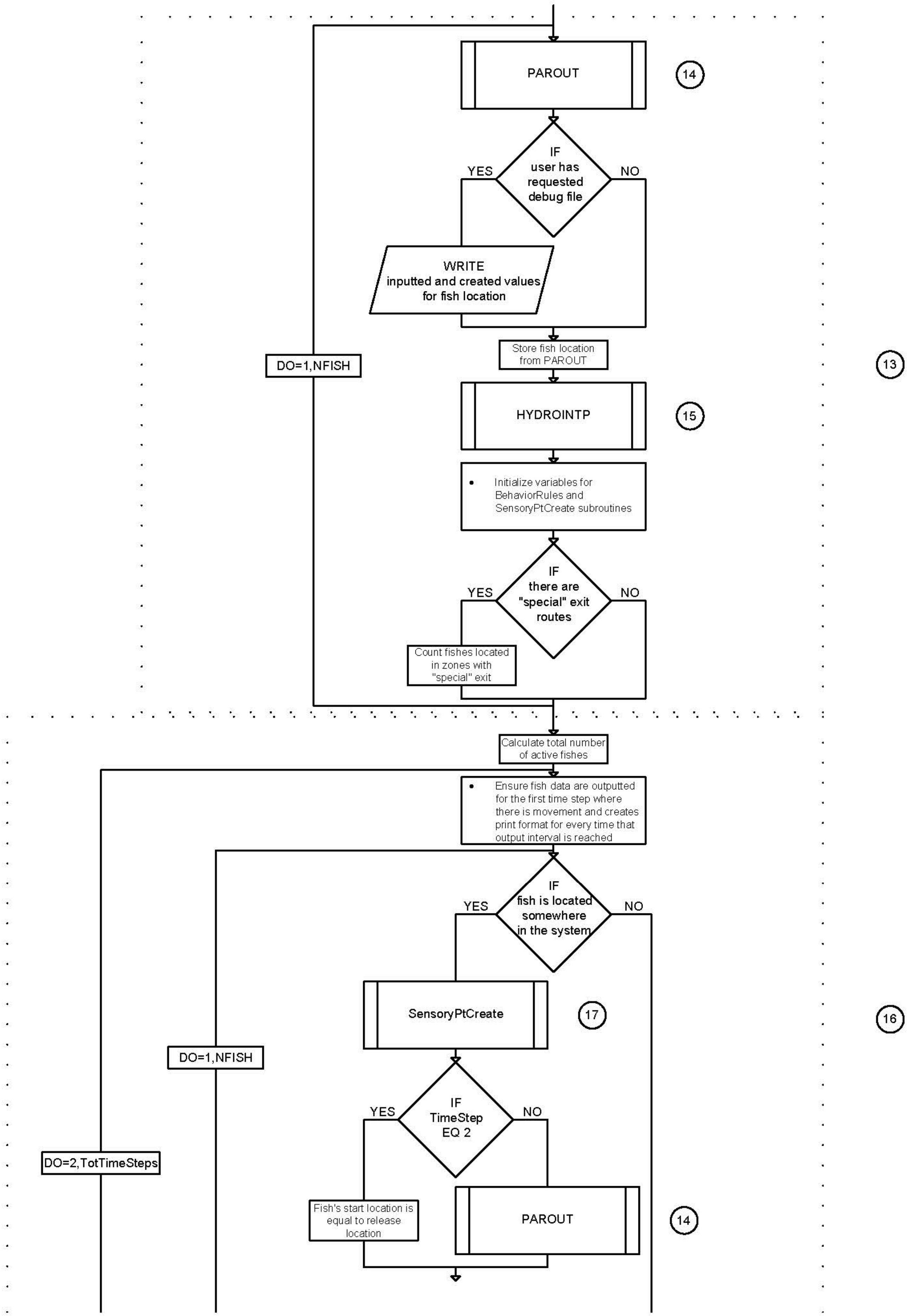
ELAM is a high complexity program with a significant size, almost 7,000 lines of code, consisting of 22 subroutines and a Driver. Undoubtedly, perception of every aspect of the program is a rigorous task, which is illustrated in current chapter. In the previous section subroutines were presented, explained and tied to the respective environmental procedures. In the following pages Driver's structure is tried to depicted by a schematic representation (scribble flowchart), while exact flowchart would be extremely extensive and merely worthless to the purposes of this study.

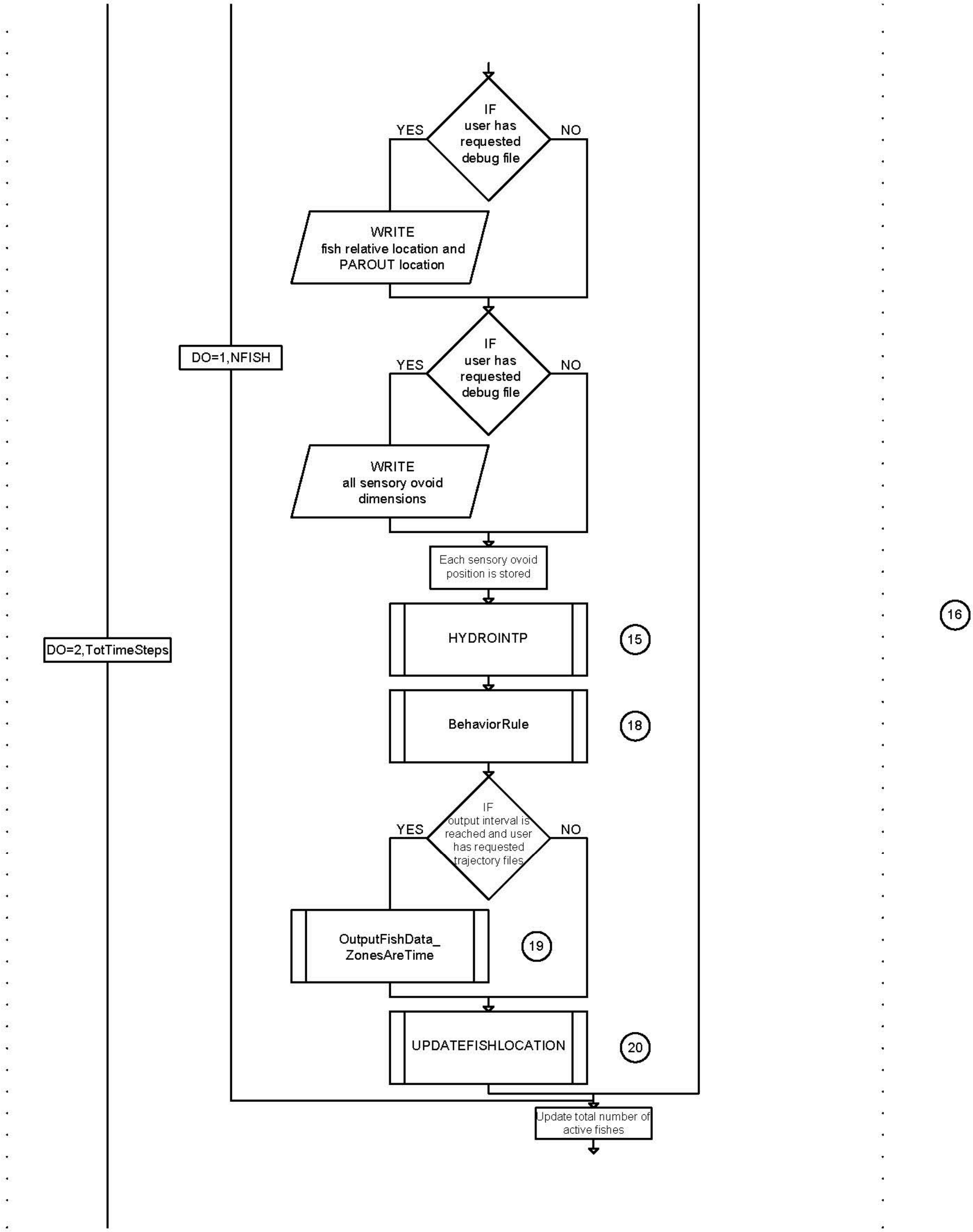
The whole depiction of the chart cannot be done in a one-page presentation, so it is allocated to current as well as to following four pages.

Figure 3.2 - 1: Scribble flowchart

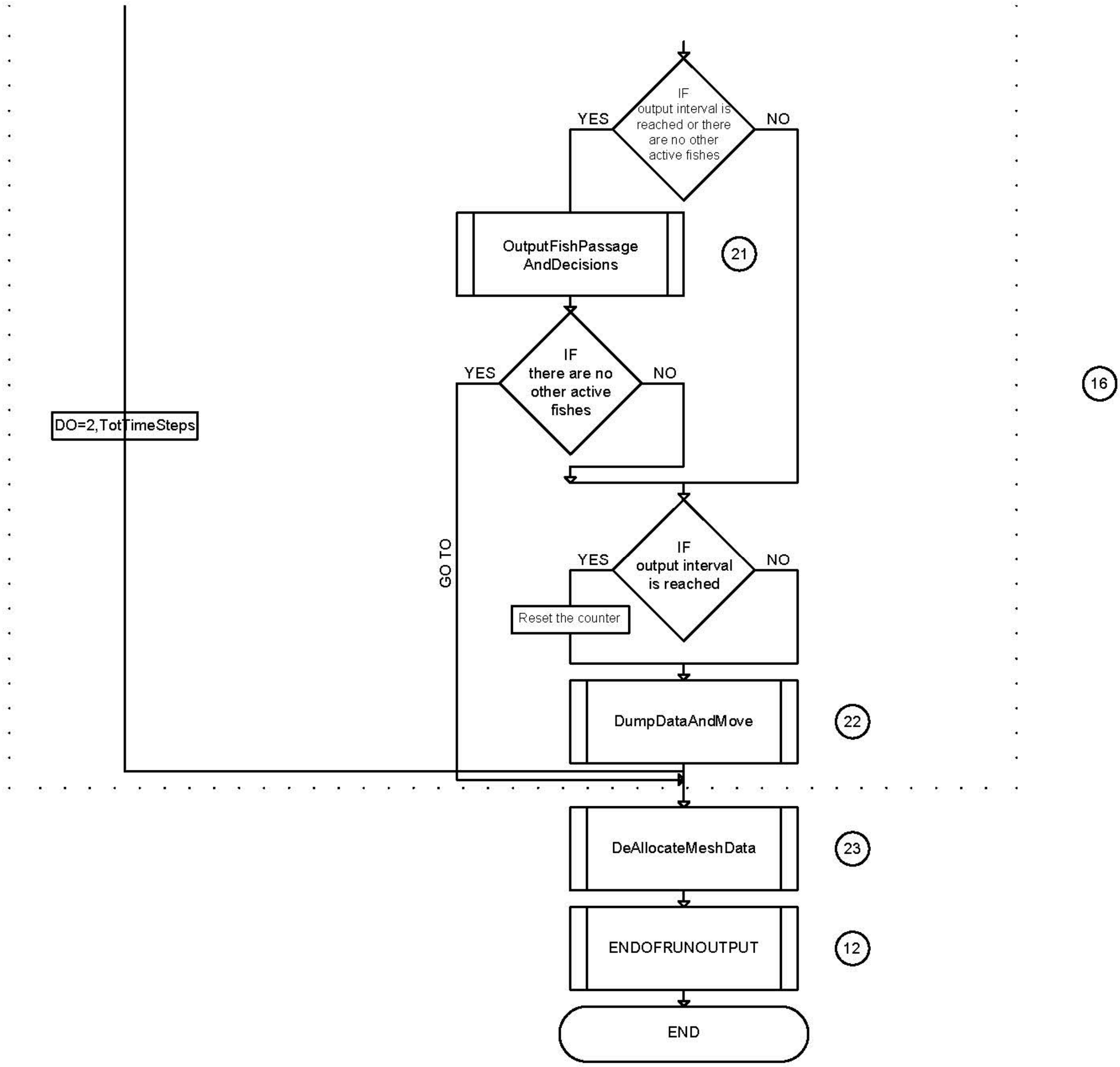



Variables initialization
Set extended limits for CFD mesh regarding fish release locations
Calculate search delta
READ
Fish Release Location
Initialize values needed in conversion of locations from Cartesian to contravariant space
YES
IF fish is in the temporary Zone
NO
DO=1,NZONES
SEARCH
11
DO=1,NFISH
YES
IF fish is out of Zone limits
NO
Count the fish
10
YES
IF temp fish value is LE count of fish loops
NO
GO TO
Store fish values
GO TO
YES
IF temp fish value is EQ count of fish loops
NO
Store out of bound fishes
YES
IF count of fish loops EQ 0
NO
ENDOFRUNOUTPUT
12


PAROUT
14
IF
user has
requested
debug file
YES
NO
WRITE
inputted and created values
for fish location
Store fish location
from PAROUT
DO=1,NFISH
13
HYDROINTP
15
Initialize variables for
BehaviorRules and
SensoryPtCreate subroutines
IF
there are
"special" exit
routes
YES
NO
Count fishes located
in zones with
"special" exit
Calculate total number
of active fishes
Ensure fish data are outputted
for the first time step where
there is movement and creates
print format for every time that
output interval is reached
IF
fish is located
somewhere
in the system
YES
NO
SensoryPtCreate
17
16
DO=1,NFISH
IF
TimeStep
EQ 2
YES
NO
DO=2,TotTimeSteps
Fish's start location is
equal to release
location
PAROUT
14



IF user has requested debug file
YES
NO
WRITE fish relative location and PAROUT location
DO=1,NFISH
IF user has requested debug file
YES
NO
WRITE all sensory ovoid dimensions
Each sensory ovoid position is stored
HYDROINTP
15
16
DO=2,TotTimeSteps
BehaviorRule
18
IF output interval is reached and user has requested trajectory files
YES
NO
OutputFishData_ ZonesAreTime
19
UPDATEFISHLOCATION
20
Update total number of active fishes



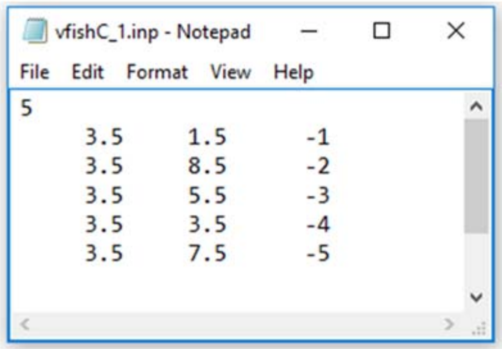
Procedures enclosed in dot boxes denoted by the respective indicator value and constitute the "Other Processes" parts explained in the previous section.

3.3 Input files

Input files for the ELAM model include several files with different extensions, structures and roles. All these, essential to completion of the simulation, files are presented in this section. Data depicted in figures below are extracted from the application presented in the next chapter.

◇ **`vfishC_1.inp`**

Lists the xyz-positions where each particle will start, i.e. the fish release locations. The letter C stands for composite (day & night) distribution, this distinction facilitates the comparison with observed data. There are also D and N types for daytime and nighttime distribution, respectively. Additionally, the number indicator denotes the serial of the file, when more than one fish release location files exist.


vfishC_1.inp - Notepad

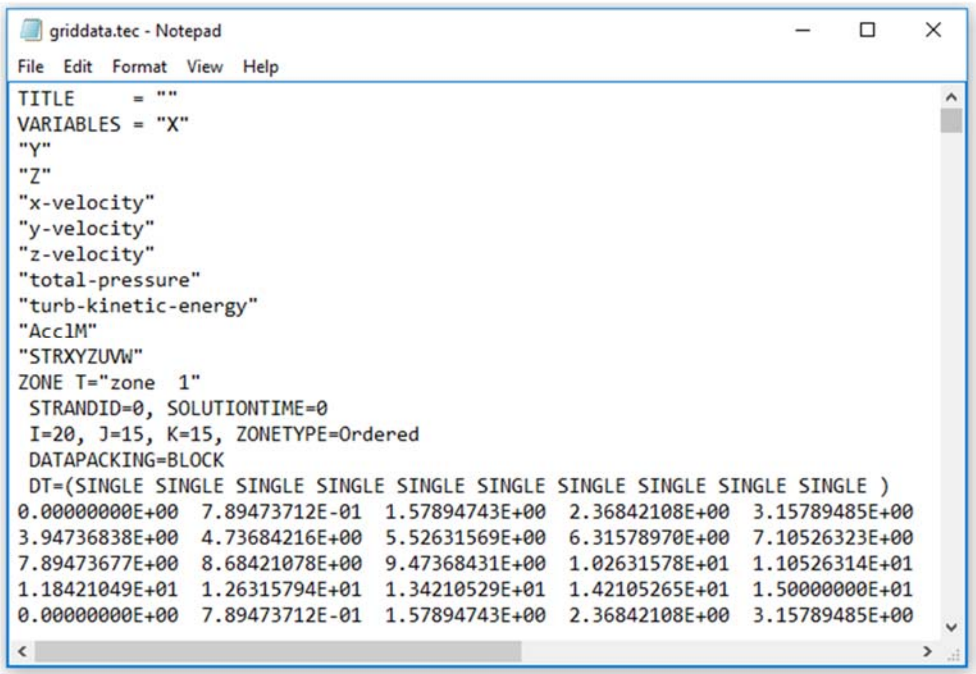
File Edit Format View Help

```
5
      3.5      1.5      -1
      3.5      8.5      -2
      3.5      5.5      -3
      3.5      3.5      -4
      3.5      7.5      -5
```

Figure 3.3 - 1: Fish release location file

◇ **`zone1.hyd`**

Hydraulic data is stored in the form of binary flow data (*.hyd) files, one file for each zone of the structured 3-D mesh. These files are generated from two files provided by the CFD model: griddata.tec and connect.asc. These files are not readable with regular programs so there is no depiction, instead part of griddata.tec file is presented.


griddata.tec - Notepad

File Edit Format View Help

```
TITLE     = ""
VARIABLES = "X"
"Y"
"Z"
"x-velocity"
"y-velocity"
"z-velocity"
"total-pressure"
"turb-kinetic-energy"
"AcclM"
"STRXYZUVW"
ZONE T="zone  1"
 STRANDID=0, SOLUTIONTIME=0
 I=20, J=15, K=15, ZONETYPE=Ordered
 DATAPACKING=BLOCK
 DT=(SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE )
0.00000000E+00  7.89473712E-01  1.57894743E+00  2.36842108E+00  3.15789485E+00
3.94736838E+00  4.73684216E+00  5.52631569E+00  6.31578970E+00  7.10526323E+00
7.89473677E+00  8.68421078E+00  9.47368431E+00  1.02631578E+01  1.10526314E+01
1.18421049E+01  1.26315794E+01  1.34210529E+01  1.42105265E+01  1.50000000E+01
0.00000000E+00  7.89473712E-01  1.57894743E+00  2.36842108E+00  3.15789485E+00
```

Figure 3.3 - 2: Section of griddata.tec file, used to derive *.hyd files

◇ connect.asc

As mentioned connect.asc file includes the connectivity between each zone, as all cells are associated with their adjacent. Along with griddata.tec file they structure hydraulic data files. Moreover, this file is also used to determine the number and the dimensions of the zones composing the mesh.

```
connect.asc - Notepad
File  Edit  Format  View  Help
           2
  1   20   15   15
  2   20   15   15
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
 -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4   -4
```

Figure 3.3 - 3: Section of connect.asc file, used to derive *.hyd files

◇ v_ExitRoutes.inp

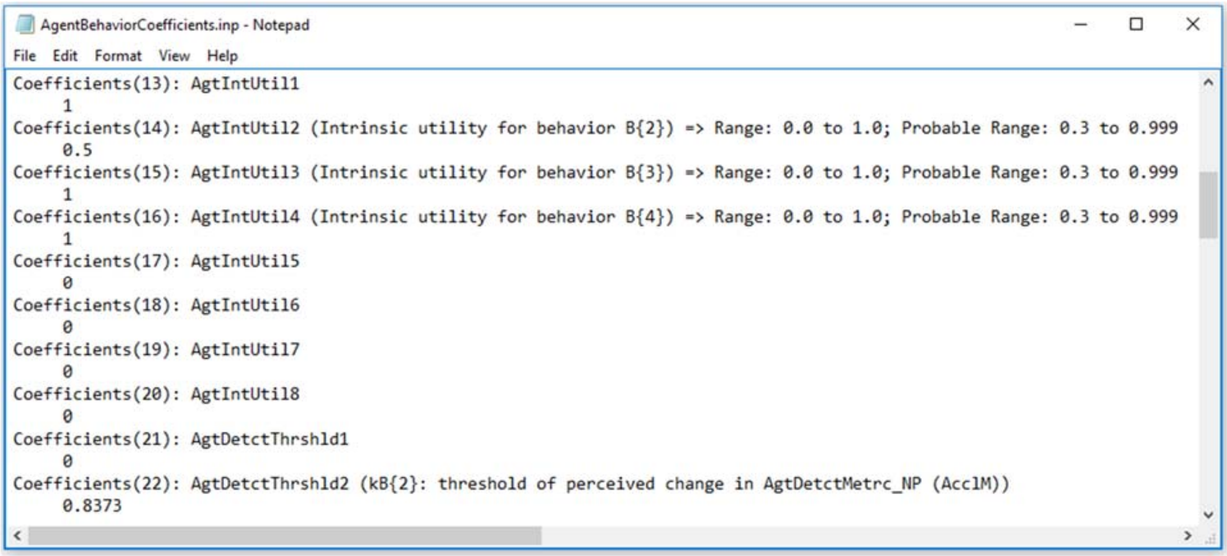
This file concerns mesh boundaries representing exit routes. It indicates where the exits for fish are located within the CFD model mesh, as well as information regarding those exits.

```
vExitRoutes.inp - Notepad
File  Edit  Format  View  Help
(A) Number of exit routes to pay 'special' attention to. Fish will be removed if/when they move into these mesh blocks/zones:
0
(B) Number of 'normal' exit routes. Fish will be removed if/when they exit these mesh blocks/zones:
2
(C) Number of mesh blocks/zones comprising each 'specialty' exit route:
    - List number of mesh blocks/zones for each route on a separate line in sequential order,
    - Next line is comment (D) if (A) is zero.
(D) Number of mesh blocks/zones comprising each 'normal' exit route:
    - List number of mesh blocks/zones for each route on a separate line in sequential order,
    - Next line is comment (E) if (B) is zero.
1
1
(E) Mesh block/zone IDs comprising each 'specialty' exit route:
    - List mesh blocks/zones for each route on a separate line in sequential order,
    - Next line is comment (F) if (A) is zero.
(F) Mesh block/zone IDs comprising each 'normal' exit route:
    - List mesh blocks/zones for each route on a separate line in sequential order,
    - This line is end-of-record if (B) is zero.
1
2
```

Figure 3.3 - 4: File involving exits for fish

◇ **AgentBehaviorCoefficients.inp**

In this file, all sensory and behavior coefficients are enclosed. It consists of 63 coefficients, however some of them are active for the current program.

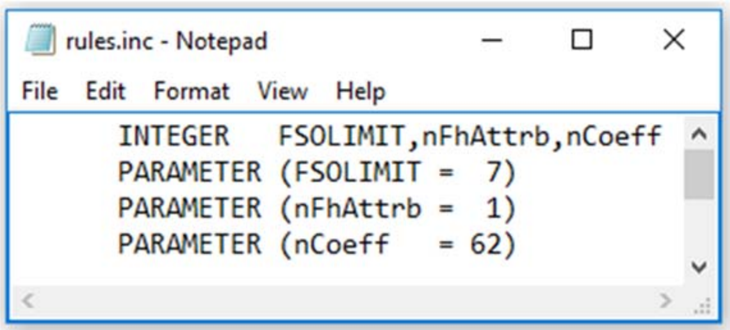



```
Coefficients(13): AgtIntUtil1
     1
Coefficients(14): AgtIntUtil2 (Intrinsic utility for behavior B{2}) => Range: 0.0 to 1.0; Probable Range: 0.3 to 0.999
     0.5
Coefficients(15): AgtIntUtil3 (Intrinsic utility for behavior B{3}) => Range: 0.0 to 1.0; Probable Range: 0.3 to 0.999
     1
Coefficients(16): AgtIntUtil4 (Intrinsic utility for behavior B{4}) => Range: 0.0 to 1.0; Probable Range: 0.3 to 0.999
     1
Coefficients(17): AgtIntUtil5
     0
Coefficients(18): AgtIntUtil6
     0
Coefficients(19): AgtIntUtil7
     0
Coefficients(20): AgtIntUtil8
     0
Coefficients(21): AgtDetctThrshld1
     0
Coefficients(22): AgtDetctThrshld2 (kB{2}: threshold of perceived change in AgtDetctMetrc_NP (AcclM))
     0.8373
```

Figure 3.3 - 5: Section of AgentBehaviorCoefficients.inp file

◇ **rules.inc**

Finally, that file is placed in the same directory with the code and determines significant elements of the program and specifically: a) number of sensory positions, b) number of fish's attribute, c) number of coefficients.




```
      INTEGER    FSOLIMIT,nFhAttrb,nCoeff
      PARAMETER (FSOLIMIT =  7)
      PARAMETER (nFhAttrb =  1)
      PARAMETER (nCoeff   = 62)
```

Figure 3.3 - 6: Rules.inp file

3.4 Output files

Output files from ELAM program includes several ASCII files, summarizing results of movement simulation. All these files are presented in this section. Data depicted in figures below are extracted from the application presented in the next chapter.

◇ **v_ExitRoutesPassageC_B_Seed92.pas**

Passage through each route at the end of simulation is summarized in this file, whose name indicates simulation settings (C for composite distribution, B for behavior rules On, 92 for the seed of random numbers). The file has as many columns as there were separate releases/simulations (i.e. one), plus one additional column at the right that sums total treatment passage as a percentage. There are as many rows as there are passage routes plus two additional rows at the bottom: the second-to-last row indicates how many simulated fish did not leave the meshed domain, and the last row indicates how many fish were simulated. This last number could be less than the number of particles released when some of the particle release positions are located outside the meshed domain.

```
v_ExitRoutesPassageC_B_Seed92.pas ...
File  Edit  Format  View  Help
        0            .0
        5         100.0
        0            .0
        5
```

Figure 3.4 - 1: Passage routes file

◇ **v_TecPassageResults.dat**

This file tallies cumulative passage each time step. The number of virtual fishes, as percentage, exiting each passage route is written-out, for every time step. Each exit is denoted with an index multiple of 3, the last row denotes fish still in calculation volume.

```
v_TecPassageResults.dat - Notepad
File  Edit  Format  View  Help
TITLE = "Passage Results (%)"
VARIABLES = "Route #", "Percent of Fish"
Zone T="Time      4.000000", I=         3, SOLUTIONTIME=       4.000000, STRA
NDID=1, F=POINT
 3.0        .0
 6.0        .0
 9.0     100.0
```

Figure 3.4 - 2: Passage results file

◇ **v_TecAgentBehaviors.dat**

This file tallies behaviors within population each time step, behavior decisions regarding each agent is printed in the file for the respective time step. The last column depicts the sum of still active fishes.

```
v_TecAgentBehaviors.dat - Notepad
File  Edit  Format  View  Help
TITLE = "Agent Behavior Decisions (%)"
VARIABLES = "TimeHrs", "PopSumAgtDecision1",          "PopSumAgtDecision2", "PopSu
 Zone T="Time       4.000000", I=1, SOLUTIONTIME=      4.000000, STRANDID=1, F=
 POINT
       .00111      .00       .00       .00       .00       .00       .00        5

 Zone T="Time       6.000000", I=1, SOLUTIONTIME=      6.000000, STRANDID=1, F=
 POINT
       .00167    100.00      .00       .00       .00       .00       .00        5
```

Figure 3.4 - 3: Agent decision file

◇ v_TecTrack_ZonesAreTime.dat

Behavior and trajectory data (organized by time) are presented here. This very file creates the visualization outcome regarding fish trajectories. This is a quite extended file, so a small section is depicted.

```
v_TecTrack_ZonesAreTime.dat - Notepad
File  Edit  Format  View  Help
TITLE = "Virtual Fish Tracks - Organized by Time"
VARIABLES = "X", "Y", "Z", "WSC", "Time", "Node BC",       "UfishCFD", "VfishCFD", "WfishCFD"
 Zone T="Time       4.000000", I=          5, SOLUTIONTIME=       4.000000, STRA
 NDID=1, F=POINT
        .349999999866E+01        .150000000060E+01        .890000000084E+01        0
        .349999998211E+01        .850000000657E+01        .789999999895E+01        0
        .350000000027E+01        .550000000409E+01        .690000000121E+01        0
        .349999998533E+01        .350000000635E+01        .590000000041E+01        0
        .350000000047E+01        .750000000243E+01        .490000000090E+01        0
```

Figure 3.4 - 4: Section of v_TecTrack_ZonesAreTime.dat file

◇ v_TecTrack_ZonesAreIndividualFish.dat

Similar to the latter, in this file also behavior and trajectory data are presented, however they are organized by individuals.

```
v_TecTrack_ZonesAreIndividualFish.dat - Notepad
File  Edit  Format  View  Help
TITLE = "Virtual Fish Tracks - Organized by Individual    Fish"
VARIABLES = "X", "Y", "Z", "WSC", "Time", "Node BC",      "UfishCFD", "VfishCFD", "Wfis
 Zone T="Fish ID#          1", I=         258, F=POINT
        .349999999866E+01        .150000000060E+01        .890000000084E+01        0
        .349999999866E+01        .150000000060E+01        .890000000084E+01        0
        .390550010429E+01        .150014589055E+01        .890005049027E+01        0
        .421506830689E+01        .156724284478E+01        .893392687295E+01        0
        .449567930743E+01        .164817085642E+01        .891260967521E+01        0
```

Figure 3.4 - 5: Section of v_TecTrack_ZonesAreIndividualFish.dat file

◇ **v_Debug.dat**

Finally, all behavior calculations, for every time step that each fish is active, are outputted in the Debug file.

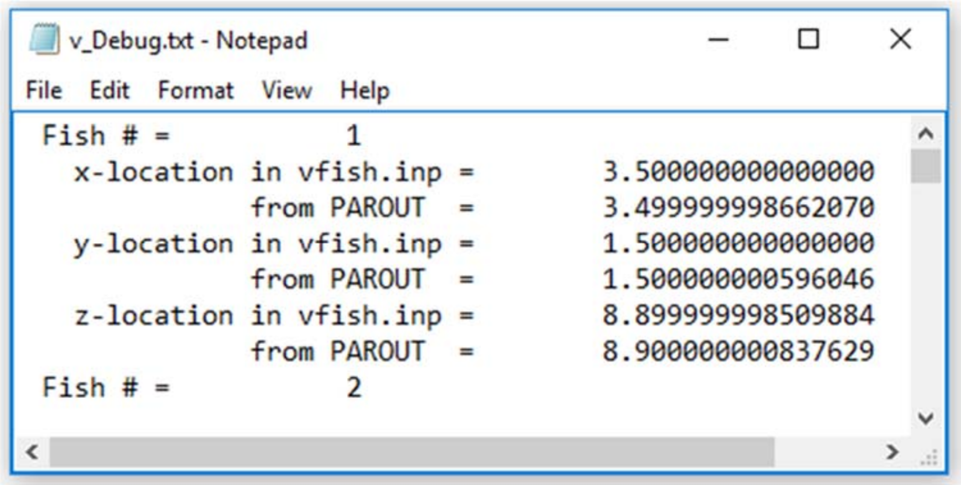


Figure 3.4 - 6: Section of Debug file

4 APPLICATION 1. CALCULATION OF SINGLE FISH TRAJECTORY

4.1 General

The present application deals with the simulation of a single virtual fish released at specific location in an orthogonal volume (30x10x10 m), as shown in Figure 4.2 - 1.

In this chapter, we present a) essential input data, b) model calculations representing environmental variables – for the first time step that there is movement – and c) calculations of fish trajectory.

4.2 Input data

The input data include the following:

1. Geometry
2. Flow data
3. Agent Behavior Coefficients
4. Fish release location

Input data 1 and 2 are inserted to the program via *.hyd files (see 3.3), while an orthogonal geometrical grid is used for the representation of the locations of input data 1, 2 and 4. The values for the Agent Behavior Coefficients obtained from the AgentBehaviorCoefficients.inp file (see 3.3); these values refer to juvenile Pacific salmonids in the Columbia/Snake River system [(Goodwin, et al., 2014), personal communication].

The visualization of the input data as well as of the results is facilitated via Tecplot 360 (http://www.tecplot.com/products/tecplot-360/).

4.2.1 Geometry

The present geometry refers to a part of a reservoir that is represented as composed by four solid boundaries, which are 3 solid/wall surfaces and the free water surface (water surface is treated as solid wall boundary), an inflow and an outflow boundary, representing a route funneling to a bypass entrance. An orthogonal mesh is used, consisting of two identical zones (1, 2), with the following dimensions:

Table 4.2 - 1: Dimensions of present grid

Indices	I	J	K
No of nodes	20	15	15
Length in meters	15	10	10

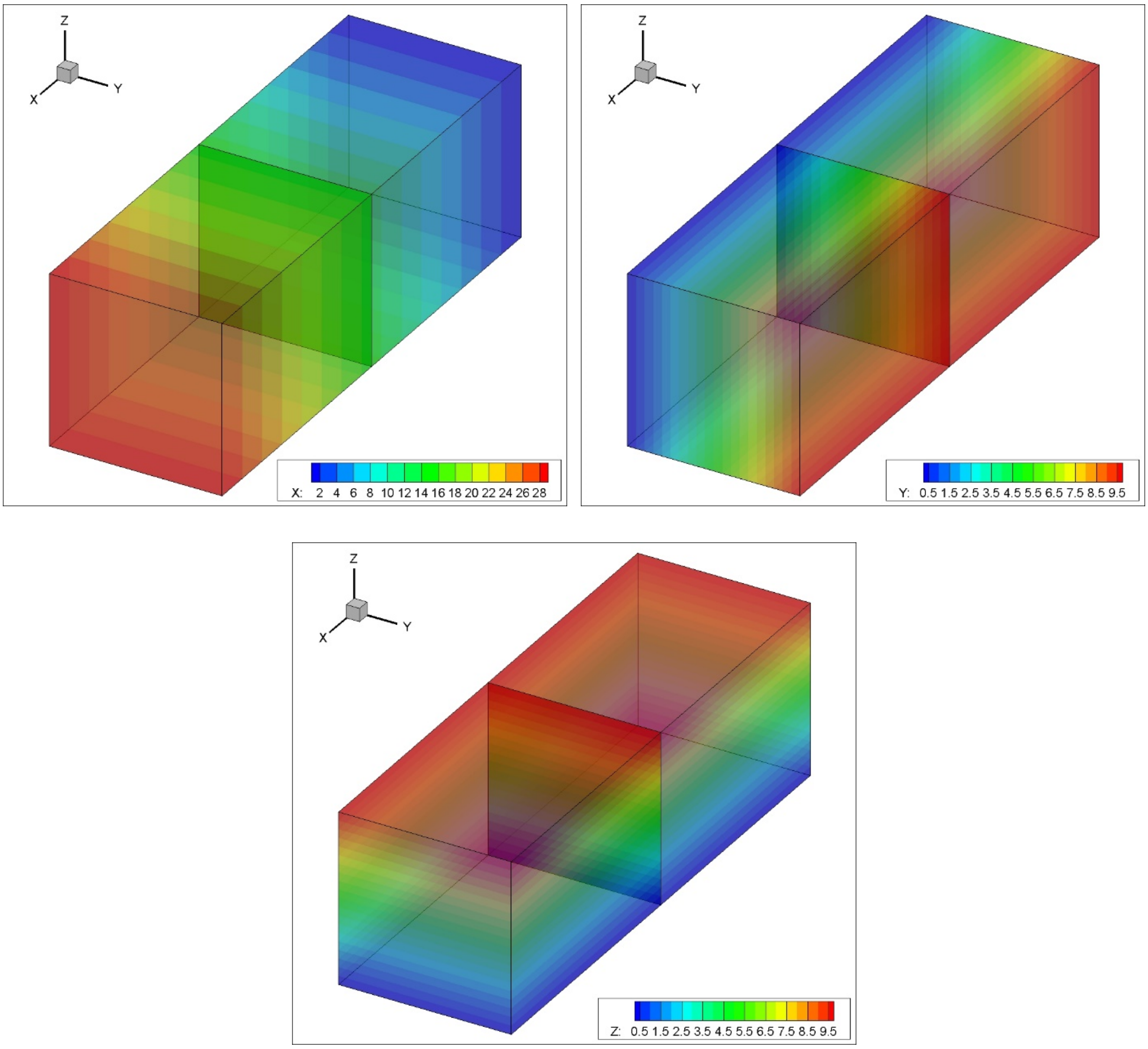


Figure 4.2 - 1: Grid structure (X, Y and Z)

4.2.2 *Flow data*

In the present application, we have employed the following steady-state flow data that we have inputted from a CFD model [(Goodwin, et al., 2014), personal communication]:

1. flow velocities (U, V and W) in m/s, and
2. flow accelerations (A) in m/s^2.

Moreover, we assumed that the total pressure is hydrostatic. In a more advance version of the model, it would be possible to employ turbulent kinetic energy, total pressure and total hydraulic strain (spatial velocity gradient).

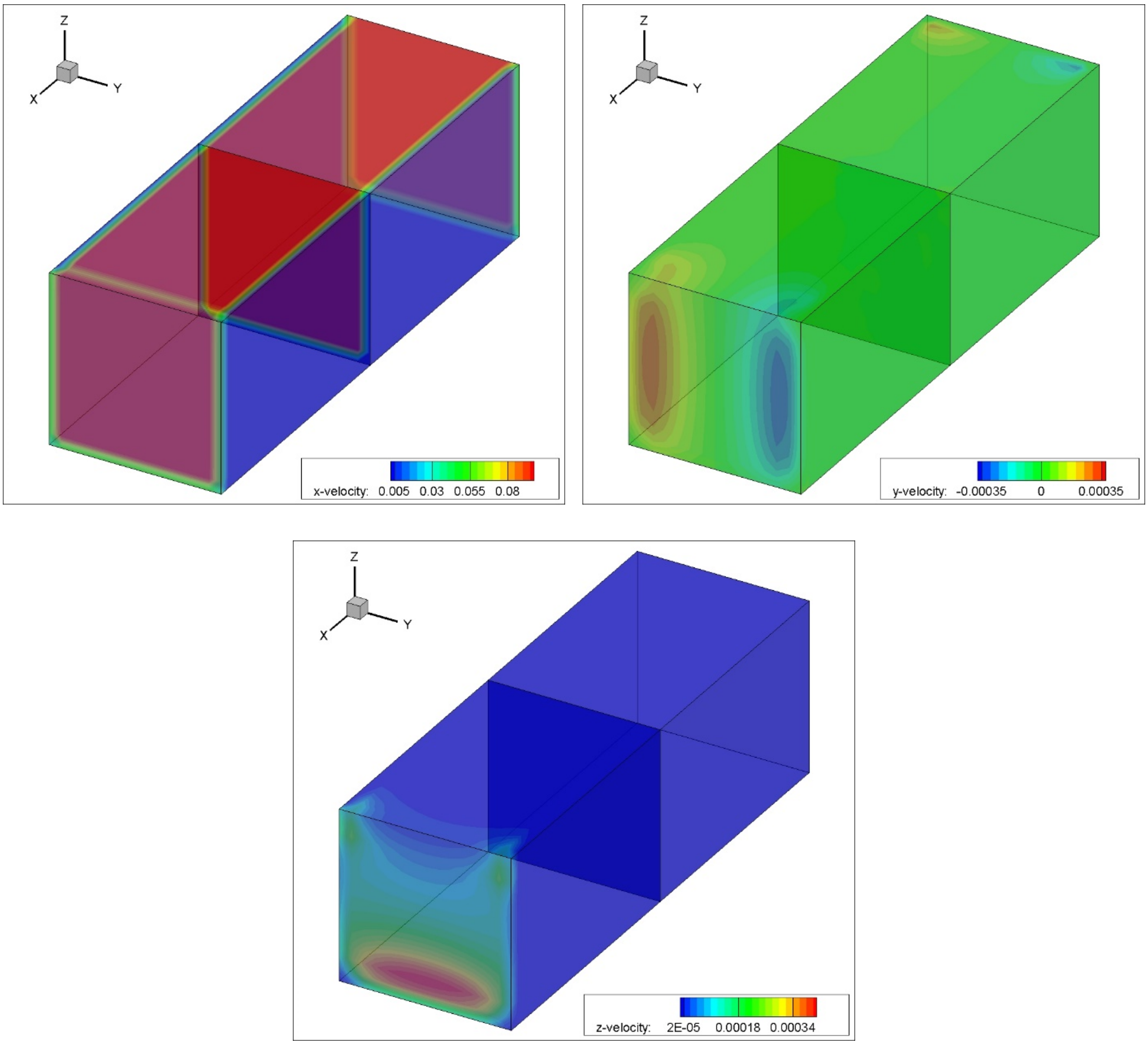


Figure 4.2 - 2: Flow velocities in X, Y and Z directions (U, V, and W)

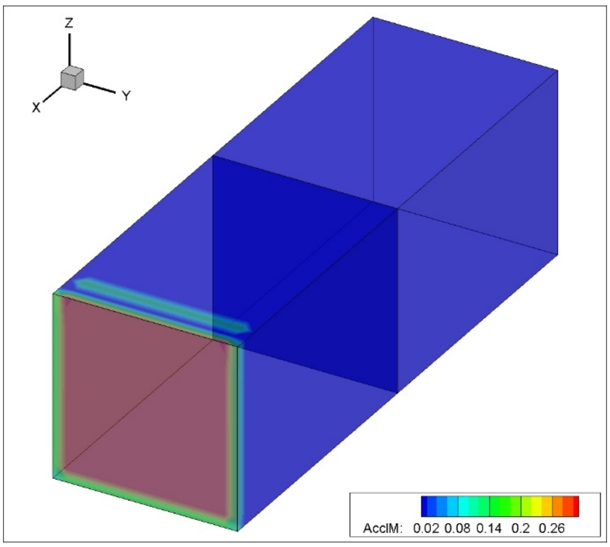


Figure 4.2 - 3: Acceleration Magnitude (A)

4.2.3 Agent Behavior Coefficients

In the model, we have used the values of the coefficients as presented in Table 4.2 - 2 along with the respective value ranges and short description; more information concerning these coefficients can be found in sections 3.1 and 3.2.

Table 4.2 - 2: Values and descriptions of the Agent Behavior Coefficients

Name	Value	Range of values	Description
C_1	4.5	0.5-10.0	$\boldsymbol{\eta}$
C_2	200.0	10.0-300.0	$\boldsymbol{\delta}$ (the value is divided by 100, when inputted)
C_3	0.25	0.001-0.999	Agent Probability, probability value for 1st time step; will also become value of Agent Utility for the default agent if Agent Memory 1 = 1.0
C_4	8	-	Number of agents, it allocates values for 8 agents, however in this model 4 out of 8 are used
C_5	1	-	Memory coefficient for behavior B{1}
C_6	0	0.0-1.0	Memory coefficient for behavior B{2}
C_7	0.9985	0.0-1.0	Memory coefficient for behavior B{3}
C_8	0.9	0.0-1.0	Memory coefficient for behavior B{4}
C_{13}	1	-	Intrinsic utility for behavior B{1}
C_{14}	0.5	0.0-1.0	Intrinsic utility for behavior B{2}
C_{15}	1	0.0-1.0	Intrinsic utility for behavior B{3}
C_{16}	1	0.0-1.0	Intrinsic utility for behavior B{4}
C_{21}	0	-	Detection threshold value B{1}
C_{22}	0.8373	-	Detection threshold value B{2}
C_{23}	0.89	-	Detection threshold value B{3}
C_{24}	1.1315	-	Detection threshold value B{4}
C_{29}	0	-	Memory coefficient for updating acclimatization B{1}
C_{30}	0.9999	0.0-1.0	Memory coefficient for updating acclimatization B{2}
C_{31}	0	-	Memory coefficient for updating acclimatization B{3}
C_{32}	0.9984	0.0-1.0	Memory coefficient for updating acclimatization B{4}
C_{37}	0.9	0.0-1.0	$\boldsymbol{\beta}$
C_{39}	0	-	Activate agent-to-agent interaction (1=Yes ; 0=No)
C_{40}	0	0.0-1.0	Stochastic noise to sensory point locations by adding range of variability to non-cardinal SP locations
C_{41}	1	0.0-1.0	Fraction of xy-plane sensory point distance (from fish centroid) to use in vertical direction (SPs 6 & 7)
C_{42}	0.4	0.4-1.0	Minimum lower-bound for initial acclimatization to acceleration
C_{44}	0.005	0.0-0.7	$\boldsymbol{I}$

4.2.4 Fish release location

The location of fish release is defined by the respective value in Vfish.inp file (see 3.3), as:

Table 4.2 - 3: Fish release location, Application 1

Indices	X	Y	Z
Input Value	1.5	5.0	-3.0
Value Used in Model	1.5	5.0	6.9

The Z values receive negative values denoting the distance from the free surface. Moreover, the value is reduced by 0.1 to approximate water surface elevation at fish release.

4.3 Calculations for the first step

The route of model calculations as well as the procedures representing environmental variables – for the first time step that there is fish movement - are depicted. Initially the model receives the input data, mentioned at the previous section. Consequently, a) SEARCH subroutine identifies fish location and converts it into contravariant values, b) HYDROINTP subroutine interpolates every environmental variable to the mesh structured.

4.3.1 Creation of sensory points

Fish sensory ovoid is shaped via 6 sensory rays surrounding and 1 on the centroid. Sensory points are placed in space as:

1. The fish itself,
2. (+ X) in the direction the head of the fish is pointing,
3. (- X) in the direction of the fish's tail,
4. (+ Y) to the left of the fish,
5. (- Y) to the right of the fish,
6. (+ Z) in the direction above the fish (parallel to gravity),
7. (- Z) in the direction below the fish (direction of gravity).

The sensory points (2-7), excluding the centroid, are determined as the displacement from the location of the fish (1), using 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 (RAND) (see 3.1).

$$SPDIST = \frac{4.5}{Log_{10}\left(\frac{0.000217}{0,000001}\right)} = 1.9262 \quad (3.1 - 3)$$

$$RINC = 1 + 0.9751329 * 2 = 2.9503 \quad (3.1 - 4)$$

$$RAND = (2 * 0.9751329 - 1) * 0 = 0 \quad (3.1 - 520)$$

In (3.1-3) the value of acceleration is used, greater or equal to 0.0001 m/sec^2. In this case water acceleration is above threshold value, thus the field value is used. So, the following values regarding sensory points defined:

Table 4.3 - 1: Sensory points as displacement distances from fish's location

Sensory point #2
Sensory Ovoid X = 5.68287
Sensory Ovoid Y = 0
Sensory Ovoid Z = 0
Sensory point #3
Sensory Ovoid X = -5.68287
Sensory Ovoid Y = 0
Sensory Ovoid Z = 0
Sensory point #4
Sensory Ovoid X = 0
Sensory Ovoid Y = 5.68287
Sensory Ovoid Z = 0

Sensory point #5
Sensory Ovoid X = 0 Sensory Ovoid Y = -5.68287 Sensory Ovoid Z = 0
Sensory point #6
Sensory Ovoid X = 0 Sensory Ovoid Y = 0 Sensory Ovoid Z = 5.68287
Sensory point #7
Sensory Ovoid X = 0 Sensory Ovoid Y = 0 Sensory Ovoid Z = -5.68287

4.3.2 Calculate next position's data and fish velocity

In the beginning of second section of BehaviorRule subroutine, VectorRelation subroutine is called to determine the flow vector velocity relative to swim vector velocity. The following figures are calculated:

From interpolation we derive:

- U=1,00204E-01 m/s^2
- V=-6,95817E-08 m/s^2
- W=4,99239E-05 m/s^2

Angle of the Master Vector relative to the CFD xy-axis:

$$\boldsymbol{MVaoCFDXYZ(1) = 360 - AbsMVaoCFDXY * \left(\frac{180}{\pi}\right) = 359.9999602}$$

where:

$$\boldsymbol{AbsMVaoCFDXY = \left|arc\tan\frac{|V|}{|U|}\right| = 0.00000069}$$

Angle of the Master Vector vertical component relative to the CFD xy-plane:

$$\boldsymbol{MVaoCFDXYZ(2) = AbsMVaoCFDZ * \left(\frac{180}{\pi}\right) = 0.02854594}$$

where:

$$\boldsymbol{MVvroCFDXY = \sqrt{(U^2 + V^2)} = 0.1002045}$$

$$\boldsymbol{AbsMVaoCFDZ = \left|arc\tan\frac{|W|}{|MVvroCFDXY|}\right| = 0.00049822}$$

Angle of the Master Vector relative to the Reference Vector's xyz-axis velocity:
$\boldsymbol{MVaoRVXY = 0.0}$ (that is the angle between flow and swim vector)

Velocity of the Master Vector relative to the Reference Vector's xyz-axis velocity:

$$\boldsymbol{MVvoRVXYZ(1) = MVvroRVXY * \cos MVaoRVXYRad = 0.1002045}$$

$$\boldsymbol{MVvoRVXYZ(2) = MVvroRVXY * \sin MVaoRVXYRad = 0.0}$$

$$\boldsymbol{MVvoRVXYZ(3) = W = 0.00004992}$$

where:

$$\boldsymbol{MVvroRVXY = \sqrt{(U^2 + V^2)} = 0.1002045}$$

$$\boldsymbol{MVaoRVXYRad = MVaoRVXY * \left(\frac{\pi}{180}\right) = 0.0}$$

◇ Perception of stimulus

Firstly, the perceived change in water acceleration, E_1(t), is examined (see 3.1).

$$\boldsymbol{I_1(t) = \log_{10}\left(\frac{0.000217}{0{,}000001}\right) = 2.336} \quad (3.1 - 7)$$

$\boldsymbol{I_{\alpha_1}(t) = \log_{10}\left(\frac{0.000217}{0{,}000001}\right) = 2.336}$, that value is used for the first time step of fish movement

$$\boldsymbol{E_1(t) = 0.0} \quad (3.1 - 6)$$

$\boldsymbol{E_1(t) = 0.0 \leq DetThr_{B\{2\}} = 0.8373}$ → No event
$\boldsymbol{E_1(t) = 0.0 \leq DetThr_{B\{3\}} = 0.89}$ → No event

Thus, there were not detected agents to stimulate either B{2} or B{3}.

Afterwards, the perceived change depth, E_2(t), is examined (see 3.1).

$$\boldsymbol{E_2(t) = |8.9 - 8.9| = 0} \quad (3.1 - 9)$$

$\boldsymbol{I_{\alpha_2}(t) = Fish\,Elev}$, that value is used for the first time step of fish movement

$\boldsymbol{E_2(t) = 0 \leq DetThr_{B\{4\}} = 1.1315}$ → No event

Thus, there was not detected agent to stimulate B{4}.

◇ Probability

The probability associated with each agent is calculated (see 3.1).

$$\boldsymbol{P_{B\{1\}}(t) = (1 - 1) * 1 + 1 * 0.25 = 0.25} \quad (3.1 - 12)$$

$$\boldsymbol{P_{B\{2\}}(t) = (1 - 0) * 0 + 0 * 0.25 = 0} \quad (3.1 - 12)$$

$$\boldsymbol{P_{B\{3\}}(t) = (1 - 0.9985) * 0 + 0.9985 * 0.25 = 0.249625} \quad (3.1 - 12)$$

$$\boldsymbol{P_{B\{4\}}(t) = (1 - 0.9) * 0 + 0.9 * 0.25 = 0.225} \quad (3.1 - 12)$$

Probability of previous time step is equal to 0.25 for every agent, as a default value for first time step of simulation.

◇ Utility

The utility associated with each agent's probability is calculated below (see 3.1).

$$U_{B\{1\}}(t) = 0.25 * 1 - 0 = 0.25 \quad (3.1 - 13)$$

$$U_{B\{2\}}(t) = 0 * 0.5 - 0 = 0.0 \quad (3.1 - 13)$$

$$U_{B\{3\}}(t) = 0.249625 * 1 - 0 = 0.249625 \quad (3.1 - 13)$$

$$U_{B\{4\}}(t) = 0.225 * 1 - 0 = 0.225 \quad (3.1 - 13)$$

In a time step, the behavior B{1,2,3} with highest utility $U_B(t)$ is active. Hence, B{1} will be implemented in the current time step. Separately encoded vertical movement B{4} is implemented when $U_{B\{4\}} \geq \beta u_{B\{4\}}$:

$U_{B\{4\}}(t) = 0.225 \leq \beta_{u_B} = 0.9$ → Not active

◇ Behavior B{1}

The default state B{1} (swim with flow vector) is a correlated random walk biased (BCRW) in the direction of downstream water flow.

Swim angle:
$$SVaoSVXY\_NP = MVaoCFDXYZ(1) - 360 = 0.00003979$$

$$SVaoCFDXYZ\_NP(2) = MVaoCFDXYZ(2) = 0.02854594$$

Swim speed:
$$S_{B\{1\}} = 0.09 * \left(2.0 + (0.1128238) * (2.0 - 0.25)\right) = 0.19776976 \quad (3.1 - 15)$$

Then the above amounts are checked if overridden from B{4}, where here this in is not the case.

◇ Convert swim angle and velocity to vectors

$$SVvoSVXYZ\_NP(1) = FhSpdResXY * \cos SVaoSVXYRad = 0.19776972$$

where:

$$SVaoCFDZRad = SVaoCFDXYZ\_NP(2) * \left(\frac{\pi}{180}\right) = 0.000498221$$

$$FhSpdResXY = S_{B\{1\}} * \cos SVaoCFDZRad = 0.197769724$$

$$SVaoSVXYRad = SVaoSVXY_{NP} * \left(\frac{\pi}{180}\right) = 0.00000069$$

Angle of the swim vector relative to the CFD xy-axis:
$$SVaoCFDXYZ\_NP(1) = SVaoSVXY\_NP = 0.00003979$$

$$SVaoCFDXYRad = SVaoCFDXYZ\_NP(1) * \left(\frac{\pi}{180}\right) = 0.00000628$$

$$SVvoCFDXYZ\_NP(1) = FhSpdResXY * \cos SVaoCFDXYRad = 0.19776972$$

$$\boldsymbol{SVvoCFDXYZ\_NP}(2) = \boldsymbol{FhSpdResXY} * \sin \boldsymbol{SVaoCFDXYRad} = \mathbf{0.00000124}$$

$$\boldsymbol{SVvoCFDXYZ\_NP}(3) = \boldsymbol{S_{B\{1\}}} * \sin \boldsymbol{SVaoCFDZRad} = \mathbf{0.00009853}$$

Angle of the swim vector relative to the flow vector xy-axis:

$$\boldsymbol{SVaoFVXY\_NP} = \boldsymbol{SVaoCFDXYZ\_NP}(\mathbf{1}) - \boldsymbol{MVaoCFDXYZ}(\mathbf{1}) = \mathbf{0.00007959}$$

Velocity of the swim vector relative to the flow vector xyz-axis velocity:

$$\boldsymbol{SVaoFVXYRad} = \boldsymbol{SVaoFVXY\_NP} * \left(\frac{\boldsymbol{\pi}}{\mathbf{180}}\right) = \mathbf{0.00000139}$$

$$\boldsymbol{SVvoFVXYZ\_NP}(\mathbf{1}) = \boldsymbol{FhSpdResXY} * \cos \boldsymbol{SVaoFVXYRad} = \mathbf{0.19776975}$$

$$\boldsymbol{SVvoFVXYZ\_NP}(\mathbf{2}) = \boldsymbol{FhSpdResXY} * \sin \boldsymbol{SVaoFVXYRad} = \mathbf{0.00000027}$$

$$\boldsymbol{SVvoFVXYZ\_NP}(\mathbf{3}) = \boldsymbol{SVvoCFDXYZ\_NP}(\mathbf{3}) - \boldsymbol{W} = \mathbf{0.00004861}$$

Fish Velocity:

$$\boldsymbol{VelMfish} = \sqrt{(\boldsymbol{SVvoCFDXYZ\_NP}(\mathbf{1})^2 + \boldsymbol{SVvoCFDXYZ\_NP}(\mathbf{2})^2 + \boldsymbol{SVvoCFDXYZ\_NP}(\mathbf{3})^2)} = \mathbf{0,1977698}$$

4.4 Calculation of the fish trajectory

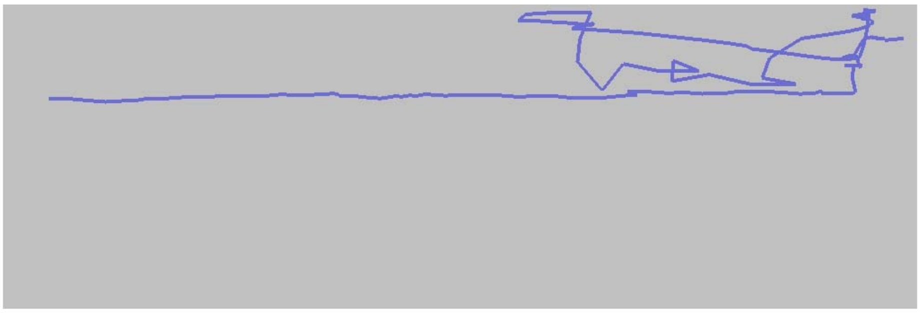
The results of the fish movement simulation are presented. Depicted are the fish trajectories from the release location until the exit of calculation domain, in three different views (Figure 4.4 - 1). The following trajectories are result of fish movement simulation, taking into account behavior rules and the respective Agent Coefficients. It is noted that the particle abandoned the route during the simulation.

Additionally, as it is obvious all four swim behaviors are activated during this simulation. More specifically, during the first half of fish movement the fish swims using a biased correlated random walk in the direction of the downstream flow until second behavior initiates almost 2.3 m before the exit. Approaching the exit route, the fish experiences water accelerations that differ from the recent past, which can cause alterations in forces from the surrounding water to the fish. There, it is perceived a change in acceleration, which exceeds the respective threshold, so the fish is oriented to swim in the direction leading to faster water irrespective of the flow direction. This attraction to velocity may reduce inertial stimuli associated with pulsations in flow from eddies and turbulence (turbulent kinetic energy) near obstacles and the water's edge. Behavior B{2} reduces exchanges of forces, facilitates downstream migration through obstacle avoidance and limits the exposure to turbulence, which is related with poor swimming efficiency and predator detection (Goodwin, et al., 2014).

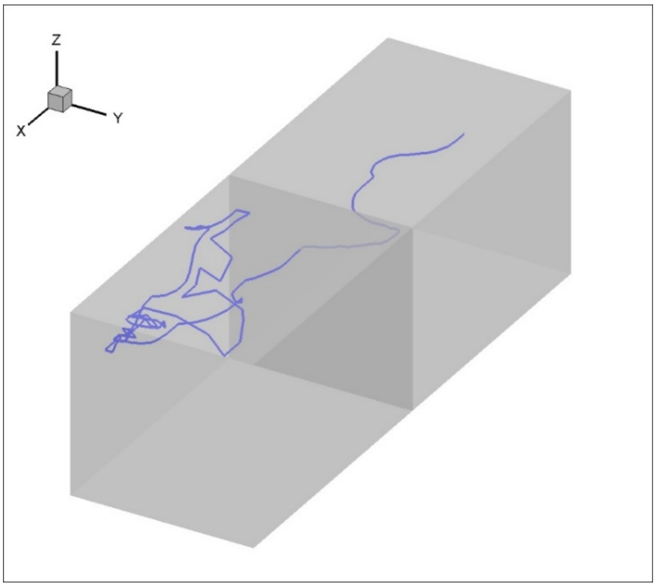
Using B{2} the fish elevates more than 2.7 m and drifts closely to the center. The outcome of the latter is that additionally to the second behavior also the fourth behavior is activated, due the significant change in fish elevation resulting a respective change in perceived pressure. While both these behaviors are active the fish is oriented to the faster water and simultaneously is oriented toward the acclimatized depth. So, the fish drifts again and "corrects" by merely 0.7 m its elevation. At this position the fish exposed to a greater change in accelration, exceeding threshold value of B{3} which is activated and coexists with B{4} for a while, as the elevation continued to decline. The activation of B{3} results to abondonment of downstream migration and beginning of upstream swimming. After fish elevation decreased for almost 1 m more and moved about 3 m upstream, B{4} deactivated and fish continued using only B{3}. Via B{3} the fish turned backwards for 9 m until perception of significant changes in acceleration stoped. There all behaviors but B{1} were deactivated. Although it should be mentioned that during the last movement the fish has elevated significantly and also reached the maximum backward position depicted (excluding the relase location).

Afterwards, for few time steps the B{1} oriented the fish to an elevation mitigation and upstream direction, until B{4} interferes again. The fish swimed upstream reducing its elevation almost a meter until the B{4} deactivated, while flactuating in y direction. Finally, after approaching the outlet exit route (~2.2 m) the fish experienced accelaration changes that triggered B{2} again. Using the latter behavior the fish abondoned the calculation volume through the outlet and the simulation terminated.

X-Y view



X-Z view



3D view

Figure 4.4 - 1: Fish trajectory, Application 1

5 APPLICATION 2. EFFECT OF FLOW DATA AND SEED ON SINGLE FISH TRAJECTORY

5.1 Examined scenarios

At this section are presented applications regarding different hydraulic and other input data, in order to explore the behavior of the model. Firstly, series of applications are depicted, where included a variety of hydraulic grids (different accelerations and velocities) to assess the respective impact of those alterations. It is highlighted that a section of relatively high accelerations is placed in the middle of the examined geometry, to investigate the effects before and after this surface of accelerations. To facilitate comparison and comprehension reasons one fish with the same release location (Table 5.1 - 1) is used for the different scenarios.

Table 5.1 - 1: Fish release location, Application 2

Indices	X	Y	Z
Input Value	1.5	1.5	-1.0
Value Used in Model	1.5	1.5	8.9

Ceteris paribus, the results are presented concerning different values of acceleration magnitude and water velocities (Table 5.1 - 2). Finally, it is noted that the velocities are presented and denoted only via U velocity as it is the most significant and representative magnitude of velocities.

Table 5.1 - 2: Examined Scenarios

	Acceleration (m/s^2)		Seed	Velocity (m/s)	
	Mean	**Max**		**Mean**	**Max**
Scenario 1	1.21E-10	3.06E-09	100	9.92E-05	1.01E-04
Scenario 2	1.21E-07	3.06E-06	100	9.92E-05	1.01E-04
Scenario 3	1.21E-06	3.06E-05	100	9.92E-05	1.01E-04
Scenario 4	1.21E-05	3.06E-04	100	9.92E-05	1.01E-04
Scenario 5	1.21E-05	3.06E-04	200	9.92E-05	1.01E-04
Scenario 6	1.21E-05	3.06E-04	300	9.92E-05	1.01E-04
Scenario 7	1.21E-05	3.06E-04	400	9.92E-05	1.01E-04
Scenario 8	1.21E-05	3.06E-04	500	9.92E-05	1.01E-04
Scenario 9	1.21E-05	3.06E-04	100	9.92E-02	1.01E-01
Scenario 10	1.21E-05	3.06E-04	100	9.92E-01	1.01
Scenario 11	1.21E-05	3.06E-04	100	9.92*	10.1*

*nonrealistic values; only for comparison and demonstration purposes

5.2 Effect of acceleration - Scenarios 1, 2, 3 and 4

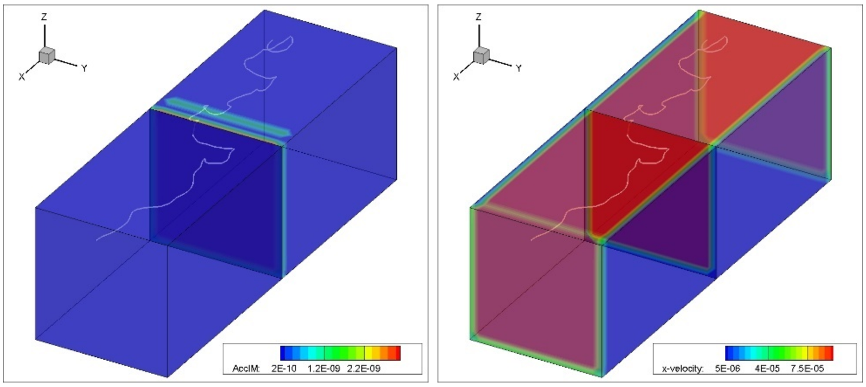
In scenario 1 (base scenario) the very low values of acceleration (~10^{-9}) in combination with the low values of water velocities (~10^{-5}) cannot trigger any of the behavior B{2}, B{3} and B{4}. Therefore, the virtual fish moves only by B{1} and exits the calculation domain via the outlet exit route after 272 seconds, as shown in Figure 5.2-1a.

In scenario 2, in which we increase the initial values of accelerations by 1.000 times, the fish follows the same trajectory as in Scenario 1, as shown in Figure 5.2-1b, i.e. its behavior remains unaffected.

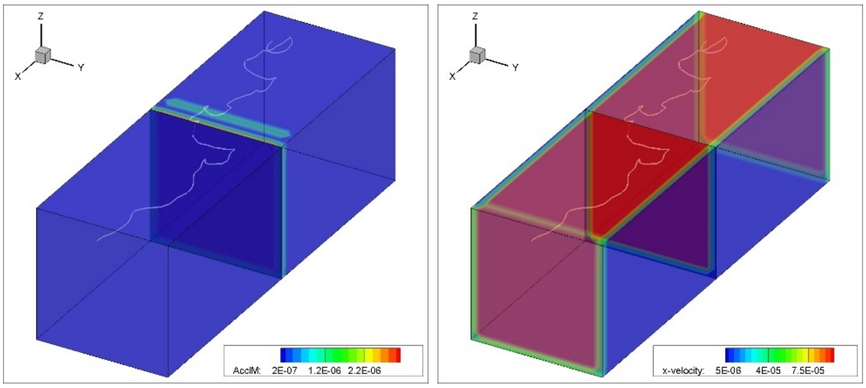
In scenario 3, initial accelerations are further increased by 10.000 times, and the virtual fish exits the calculation domain via the outlet section after 356 seconds, following a prolonged movement by 30% compared to scenario 1 (Figure 5.2-1c). This longer trajectory is due to the fact that the specific acceleration magnitude increase triggers behavior B{2}, which drives the fish towards faster water regions.

In scenario 4, initial accelerations are increased by 100.000 times, both behaviors B{2} and B{3} are activated, behavior B{3} prevails and subsequently the fish abandons the downstream migration due to high accelerations, orients upstream and exits the calculation domain via the inlet section (upstream) after 208 seconds (Figure 5.2-1d).

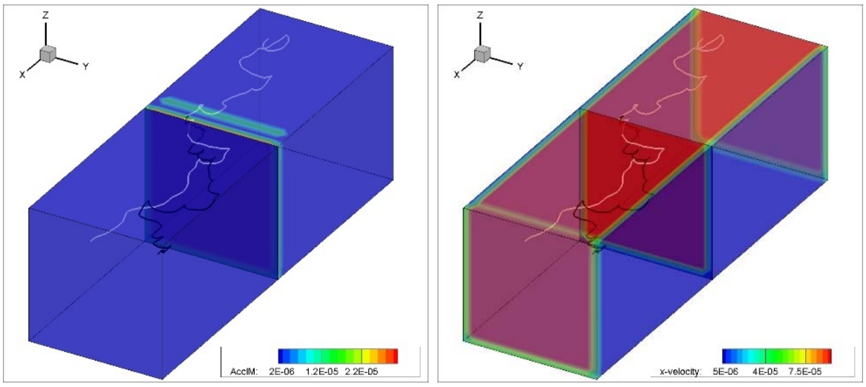
Black and white trajectories denote current and base scenario, respectively.



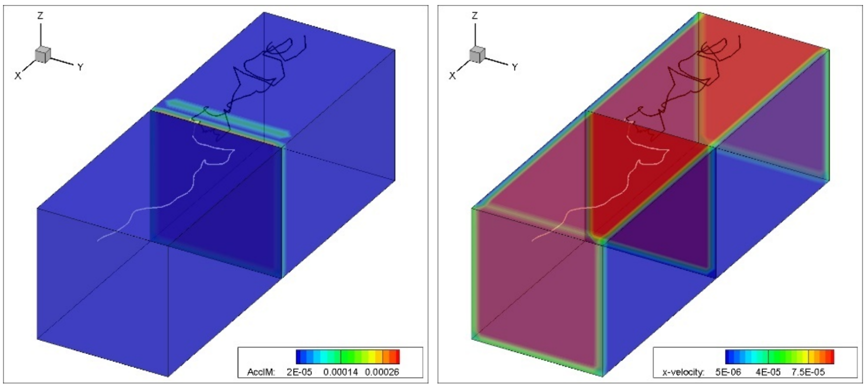
(a)Scenario 1



(b)Scenario 2



(c)Scenario 3



(d)Scenario 4

Figure 5.2 - 1: Calculation results, effect of acceleration (Scenarios 1, 2, 3 and 4)

5.3 Effect of seed number - Scenarios 5, 6, 7, and 8

Hydraulic data of the base scenario 4 (acceleration ~10^{-4} and velocities ~10^{-5}) are used in combination with altered seed number for scenarios 5, 6, 7 and 8.

In scenario 5, a seed (random number) equal to 200 is used, driving the fish to exit the calculation domain via the outlet section after 526 seconds (Figure 5.3- 2a), in contrast to base scenario where fish oriented upstream. Moreover, no event observed during the movement; the virtual fish moved only by behavior B{1}.

In scenarios 6, 7, and 8 initial seed number changed to 300, 400 and 500 respectively, resulting in fish exiting via the inlet section (upstream), as in base scenario. In all three scenarios behaviors B{2,3} were also involved in fish orientation (Figure 5.3- 2b, c & d). Changes in movement duration (Scenario 6=224 sec, Scenario 7=452 sec and Scenario 8=356 sec) are caused by differences in prevailed behaviors for each scenario.

The most prolonged route is observed in Scenario 7 (Figure 5.3 - 1), which caused by repeated attempts for downstream passage. Fish may evaluate several times the same passage before choose to select or reject it.

Black and white trajectories denote current and base scenario, respectively.

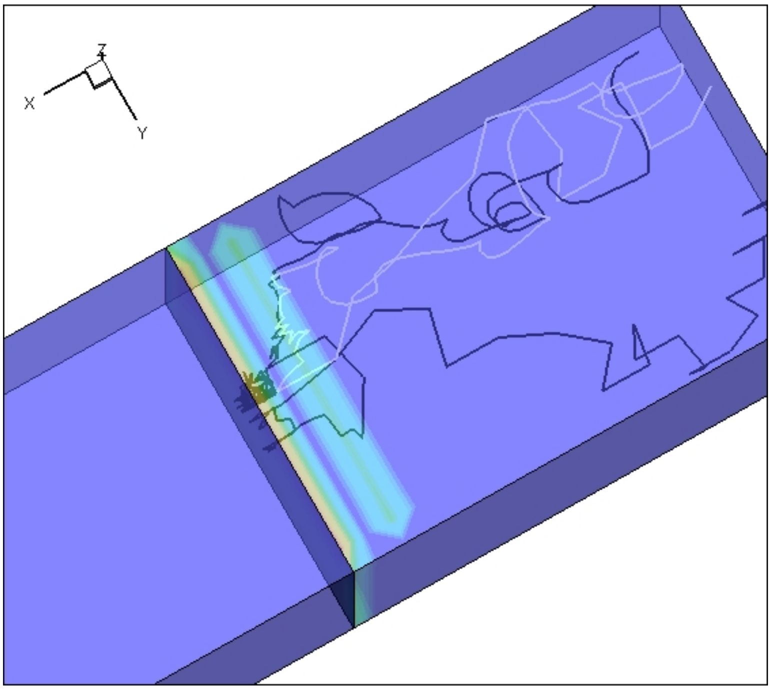
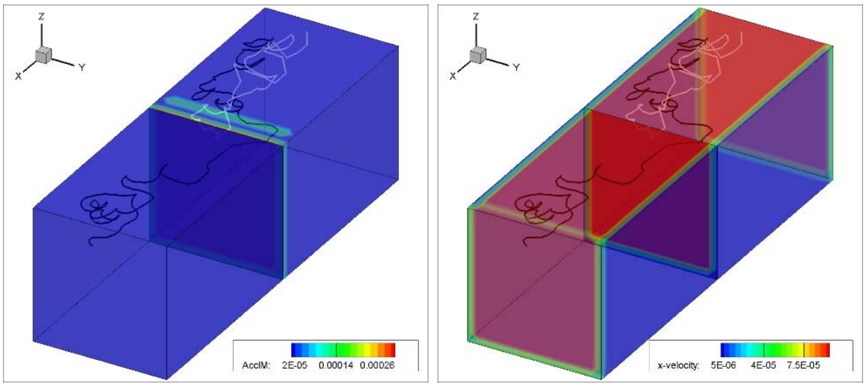
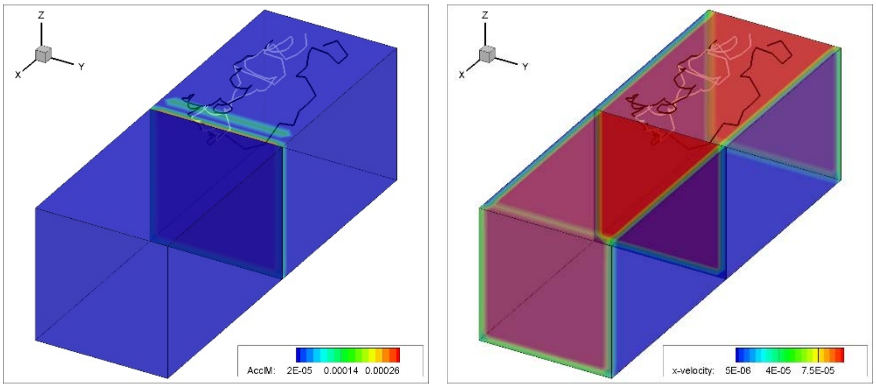


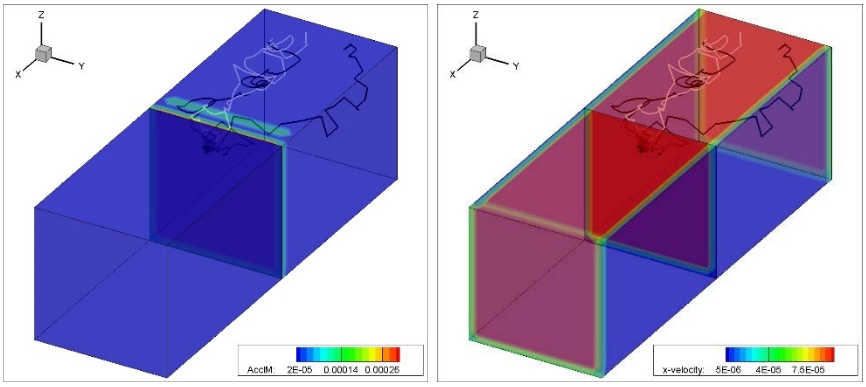
Figure 5.3 - 1: Several attempts for downstream passage, Scenario 7



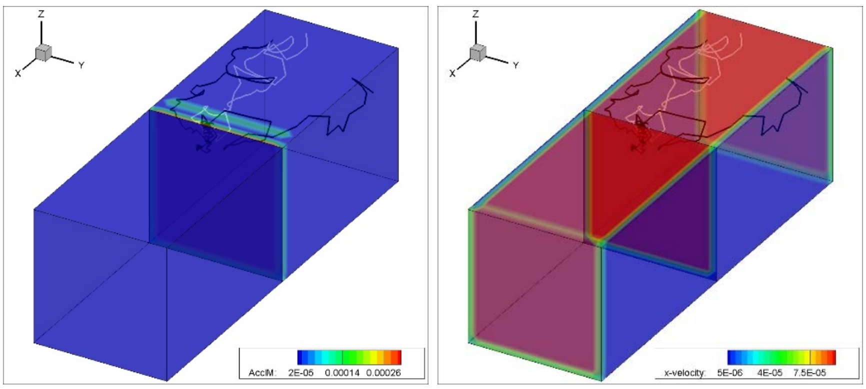
(a)Scenario 5



(b)Scenario 6



(c)Scenario 7



(d)Scenario 8

Figure 5.3 - 2: Calculation results, effect of seed (Scenarios 5, 6, 7 and 8)

5.4 Effect of flow velocity - scenarios 9, 10 and 11

In the examination of the effect of flow velocity, scenario 4 (acceleration ~10^{-4} and velocities ~10^{-5}) is used as the base scenario.

In scenario 9 values of water velocities increased by 1.000 times, driving the fish to exit the calculation domain via upstream inlet section after 540 seconds, following a longer trajectory by merely 100% compared to scenario 4. This prolonged trajectory caused by a greater "effort" to continue downstream passage (Figure 5.4 - 1) due to the increased flow velocity, as shown in Figure 5.4-2a. During this scenario behaviors B{1,2,3,4} are involved in fish orientation.

In scenario 10 values of water velocities increased further by 10.000 times. Fish movement was highly influenced as the fish exit the calculation volume via the outlet after 40 seconds; an enormous reduction in movement duration as consequence of high velocities (Figure 5.4-2b). During this scenario behaviors B{1,2,3} are involved.

In scenario 11 values of water velocities increased by 100.000 times; a nonrealistic scenario, used only for comparison and demonstration purposes (Figure 5.4-2c). Every behavior response is eliminated probably due to the fact that perception procedure at these water velocities is impossible. The fish moved solely via B{1} pure "flow convection", exiting the outlet after 5 seconds.

Black and white trajectories denote current and base scenario respectively.

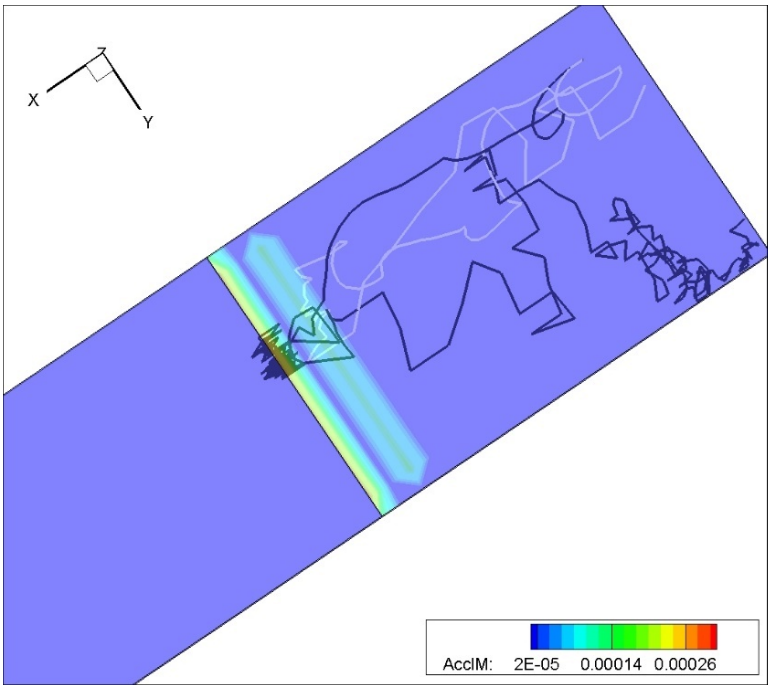
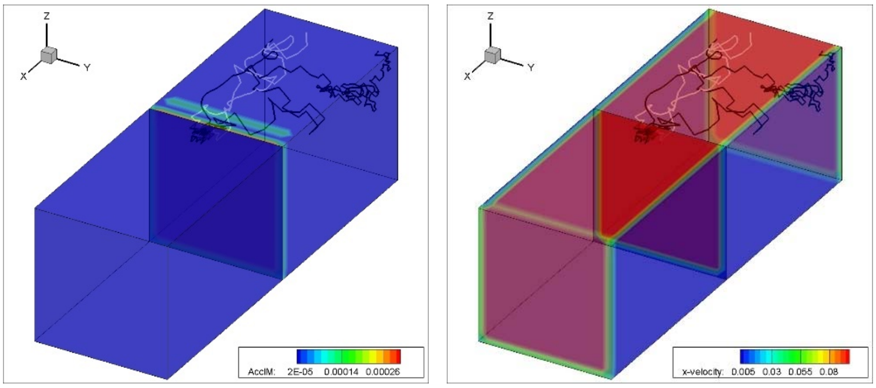
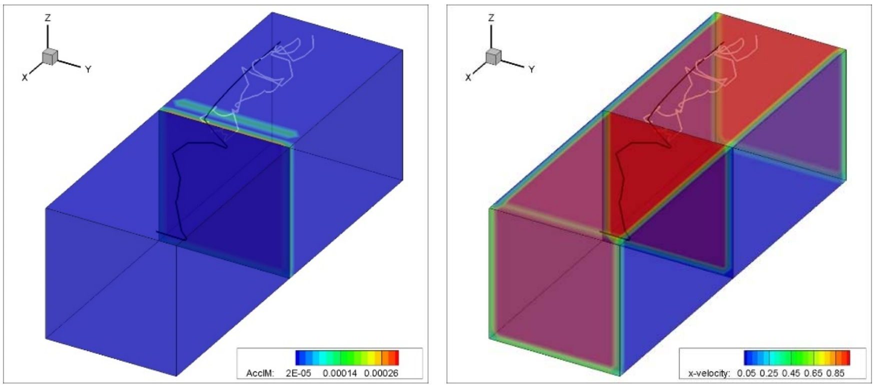


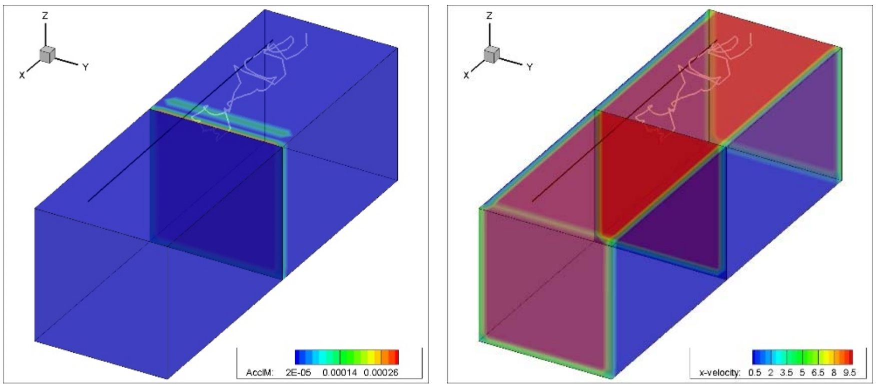
Figure 5.4 - 1: Several attempts for downstream passage, Scenario 9



(a)Scenario 9



(b)Scenario 10



(c)Scenario 11

Figure 5.4 - 2: Calculation results, effect of flow velocity (Scenarios 9, 10 and 11)

6 SENSITIVITY ANALYSIS

Sensitivity analysis calculations have been performed for 100 fishes and 9 scenarios-combinations of velocities-accelerations, which involved 3 scenarios of low, medium and high values of velocities and 3 analogous scenarios of accelerations; these are shown in Table 6 - 1. In all runs, we calculated the number of fishes passing through the outlet. This sensitivity analysis consists of more than 120 runs.

Table 6 - 1: Values of velocities and accelerations of the 9 scenarios

	Acceleration (m/s^2)			Velocity (m/s)	
	Mean	**Max**		**Mean**	**Max**
A-LOW	0.003	0.102	U-LOW	0.034	0.101
A-MEDIUM	0.008	0.306	U-MEDIUM	0.068	0.202
A-HIGH	0.024	0.919	U-HIGH	0.101	0.303

The analysis was performed in 2 steps. In the first step, calculations were performed for the combinations (1) A-LOW and U-MEDIUM and (2) A-HIGH and U-MEDIUM and the results are presented in Table 6 - 2.

Table 6 - 2: Passage results for the combinations (1) A-LOW and U-MEDIUM and (2) A-HIGH and U-MEDIUM

		A-LOW and U-MEDIUM			A-HIGH and U-MEDIUM		
Coefficient		**Pass**	**Return**	**Still active**	**Pass**	**Return**	**Still active**
Default		100	0	0	99	1	0
Coefficient 1	0.5	100	0	0	99	1	0
	10.0	100	0	0	97	3	0
Coefficient 2	10.0	100	0	0	100	0	0
	300.0	100	0	0	99	1	0
Coefficient 3	0.001	59	41	0	7	93	0
	0.999	100	0	0	100	0	0
Coefficient 6	1.0	100	0	0	100	0	0
Coefficient 7	0.0	80	0	20	82	0	18
	1.0	100	0	0	100	0	0
Coefficient 8	0.0	100	0	0	99	1	0
	1.0	100	0	0	99	1	0
Coefficient 14	0.0	100	0	0	100	0	0
	1.0	100	0	0	99	1	0
Coefficient 15	0.0	100	0	0	100	0	0
Coefficient 16	0.0	96	4	0	88	12	0
Coefficient 30	0.0	100	0	0	99	1	0
Coefficient 32	0.0	100	0	0	99	1	0
	1.0	100	0	0	97	3	0
Coefficient 40	1.0	100	0	0	99	1	0

From Table 6 - 2 it is depicted that the most sensitive coefficients are coefficient 3,7 and 16.

In the second step of the analysis, additional calculations were performed for coefficients 3, 7 and 16; all 9 scenarios and the results are depicted in Table 6 - 3.

Table 6 - 3: Passage results for all scenarios

Default	**A-LOW**	**A-MEDIUM**	**A-HIGH**
U-LOW	100	91	79
U-MEDIUM	100	100	99
U-HIGH	100	100	98
Coef.3-Min			
U-LOW	48	23	4
U-MEDIUM	59	36	7
U-HIGH	72	61	22
Coef.3-Max			
U-LOW	100	100	100
U-MEDIUM	100	100	100
U-HIGH	100	100	100
Coef.7-Min			
U-LOW	24	27	30
U-MEDIUM	80	83	82
U-HIGH	100	100	100
Coef.7-Max			
U-LOW	99	92	77
U-MEDIUM	100	100	100
U-HIGH	100	100	100
Coef.16-Min			
U-LOW	84	74	83
U-MEDIUM	96	93	88
U-HIGH	98	97	99

From the present sensitivity analysis, the following conclusions are drawn:

1. The most important coefficients of the model are coefficients 3, 7 and 16.

2. Coefficient 3 represents the value of utility for behavior B{1}; lower values of utility result in lower participation of behavior B{1} in fish movement and vice versa. Thus if only behavior B{1} is used, downstream passage is unaffected by environmental variables (100% passage result), otherwise impact of environmental variables in downstream migration is undoubted.

3. Coefficient 7 is the memory coefficient for behavior B{3}, integrating the amount of past information into the next decision following the notion that intensity or duration of activity in sensory neurons needs to pass a threshold to reach awareness. Consequently, lower values of memory coefficient lead to more frequent activation of behavior B{3} and vice versa. Hence, prevalence of behavior B{3} leads to significant decrease in passage results, while on the other hand downstream migration enhanced.

4. Coefficient 16 denotes the subjective intrinsic value of behavior B{4} in realizing a goal. Use of minimum value equals to permanent deactivation of this behavior.

7 CONCLUSIONS AND PROPOSED RESEARCH

7.1 Conclusions

The following conclusions are drawn from the present study:

1. The model ELAM is probably the most appropriate model from those available in the literature that can be used for fish modeling purposes in Fish-Passes.

2. A single fish can perceive

   a. stimuli from acceleration change based on "just noticeable differences", and

   b. changes in pressure proportionally to changes in depth.

Following this state, a fish can choose among the below possible behaviors:

   a. B{1}, to swim along with the flow; this consists of a Biased Correlated Random Walk (BCRW), in the direction of the flow.

   b. B{2}, to swim towards regions of faster flows thus achieving reduction of force exchange, facilitating downstream migration through obstacle avoidance and limiting exposure to turbulence.

   c. B{3}, to swim against flow vector, which is an escape response, where fish abandons downstream migration to swim upstream.

   d. B{4}, to swim vertically toward acclimatized depth; this orients swimming to acclimatized depth if not already accomplished by other behaviors.

   Behaviors B{2,3} are associated with changes in acceleration, while behavior B{4} with changes in pressure.

3. Presence of acceleration cues can trigger behaviors B{2,3}. Significant values of acceleration magnitude are essential to activate those behaviors, however, more important is the role of acceleration gradient in perception of changes.

4. Flow velocity provides no stimuli to the fish, but it can influence its trajectory; high velocities mitigate trajectory fluctuations and facilitate downstream migration.

5. The seed number may have an important effect on fish trajectory; thus, it is advisable to perform the same calculations for various seed numbers.

6. The most important coefficients of the model are coefficients 3, 7 and 16.

   a. Coefficient 3 represents the value of utility for behavior B{1}; lower values of utility result in lower participation of behavior B{1} in fish movement and vice versa.

   b. Coefficient 7 is the memory coefficient for behavior B{3}, integrating the amount of past information into the next decision. Lower values of memory coefficient lead to more frequent activation of behavior B{3} and vice versa.

   c. Coefficient 16 denotes the subjective intrinsic value of behavior B{4} in realizing a goal. Use of minimum value equals to permanent deactivation of this behavior.

7.2 Proposed research

The following research is proposed to be extended and applied in Fish-Passes. Actually, this is currently performed in the NTUA in the form of 2 MSc Theses:

1. Development of a fish model based on the present findings and combine with a CFD model to apply it in a river section including a vertical slot Fish-Pass.

2. Development of a fish model based on the present findings and combine with a CFD model to apply it at TUM-Hydro Shaft Power Plant Prototype (Oskar von Miller – Institute, Obernach; Technical University of Munich).

Figure 7.2 - 1: Vertical slot Fish-Pass, [source: (FAO, 2001)]

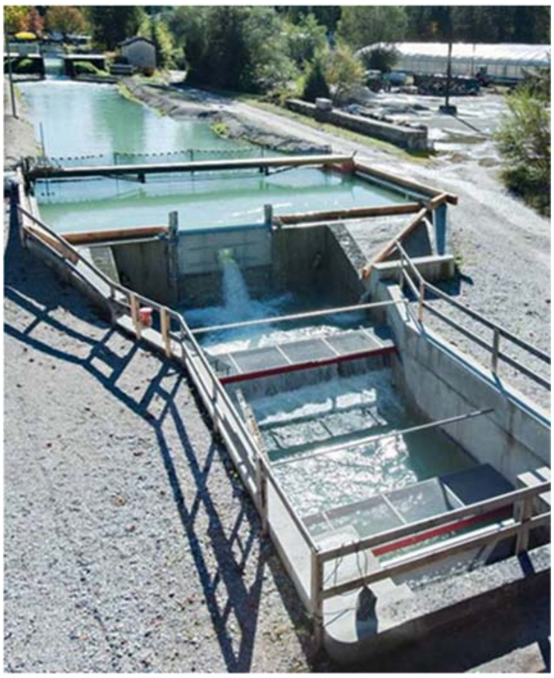


Figure 7.2 - 2: TUM-Hydro Shaft Power Plant Prototype, Oskar von Miller – Institute, Obernach [source: (Rutschmann, et al., 2016)]

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Appendix

During October 2016, we visited Oskar von Miller – Institute, Obernach - Germany, where state-of-the-art experiments are conducted regarding fish passaging, below are presented photographs from this visit.