Bifurcated Estuary Models

Core Components and Initialization

The `BifurcatedEstuaryModels` class, implemented in C#, defines a bifurcated estuarine grid with a main channel and two branches, enabling simulation of spatially varying dynamics in estuarine circulation models. It integrates with the `AsymmTidalMix` class to provide grid initialization and branch-specific adjustments for tidal velocity and turbulent mixing. The class is initialized with the following parameters:

- Number of cells in main channel: $n_{\text{main}} = 30$
- Number of cells per branch: $n_{\text{branch}} = 20$
- Estuary length: $L = 10000\,\text{m}$
- Bifurcation point: $x_b = 0.6L$ (fraction of estuary length)
- Depth scaling for branch 1: $s_{d1} = 0.8$ (shallower)
- Depth scaling for branch 2: $s_{d2} = 1.2$ (deeper)
- Tidal velocity scaling for branch 1: $s_{t1} = 0.7$ (reduced tidal influence)
- Tidal velocity scaling for branch 2: $s_{t2} = 1.3$ (enhanced tidal influence)

The constructor sets these parameters, which control the geometry and dynamics of the bifurcated estuary.

Functioning Logic

The class provides three main methods to support estuarine modeling:

1. `InitializeBifurcatedGrid`: Creates an unstructured grid with cells for the main channel and two branches, assigning coordinates, depths, areas, and neighbor connectivity.
2. `GetBranchIndex`: Identifies whether a cell belongs to the main channel or one of the branches.
3. `AdjustMixingDynamics`: Modifies turbulent viscosity and turbulent kinetic energy (TKE) production based on branch-specific depth and tidal scaling.
4. `AdjustTidalVelocity`: Scales tidal velocity at branch ends to reflect differing tidal influences.

Grid Initialization

The `InitializeBifurcatedGrid` method constructs a grid with $n_{\text{main}} + 2 \cdot n_{\text{branch}} = 70$ cells:

- **Main Channel**: $n_{\text{main}} = 30$ cells from $x = 0$ (ocean) to $x = x_b = 0.6L$.

- Cell width: $\Delta x_{\text{main}} = \frac{x_b}{n_{\text{main}}}$
- X-coordinate: $x_i = i\Delta x_{\text{main}} + \text{rand} \cdot 0.5\Delta x_{\text{main}}$, where rand $\in [0, 1)$.
- Depth: $h_i = 5.0 + 5.0 \sin\left(\frac{\pi x_i}{L}\right)$ m
- Area: $A_i = \Delta x_{\text{main}} \cdot 100 \cdot (0.8 + \text{rand} \cdot 0.4)\,\text{m}^2$

- **Branch 1**: $n_{\text{branch}} = 20$ cells from $x = x_b$ to $x = L$.
  - Cell width: $\Delta x_{\text{branch}} = \frac{L - x_b}{n_{\text{branch}}}$
  - X-coordinate: $x_i = x_b + i\Delta x_{\text{branch}} + \text{rand} \cdot 0.5\Delta x_{\text{branch}}$
  - Depth: $h_i = \left[5.0 + 5.0 \sin\left(\frac{\pi x_i}{L}\right)\right] \cdot s_{d1}$ m
  - Area: $A_i = \Delta x_{\text{branch}} \cdot 100 \cdot (0.8 + \text{rand} \cdot 0.4)\,\text{m}^2$
- **Branch 2**: $n_{\text{branch}} = 20$ cells from $x = x_b$ to $x = L$.
  - Same cell width and x-coordinate as Branch 1
  - Depth: $h_i = \left[5.0 + 5.0 \sin\left(\frac{\pi x_i}{L}\right)\right] \cdot s_{d2}$ m
  - Area: Same as Branch 1
- **Neighbor Connectivity**:
  - Main channel: Linear (cell i connects to $i - 1$ and $i + 1$), with the last cell ($i = n_{\text{main}} - 1$) connecting to the first cells of both branches.
  - Branch 1: Linear (cell i connects to $i - 1$, $i + 1$), with the first cell connecting to the bifurcation point.
  - Branch 2: Similar to Branch 1.

A fixed random seed ensures reproducibility.

Branch Identification

The `GetBranchIndex` method assigns a cell to a region:

$$\text{Branch Index} = \begin{cases} 0 & \text{if } i < n_{\text{main}} \text{ (main channel)} \\ 1 & \text{if } n_{\text{main}} \leq i < n_{\text{main}} + n_{\text{branch}} \text{ (branch 1)} \\ 2 & \text{if } i \geq n_{\text{main}} + n_{\text{branch}} \text{ (branch 2)} \end{cases} \tag{1}$$

Mixing Dynamics Adjustment

The `AdjustMixingDynamics` method modifies turbulent viscosity (ν_T) and TKE production (P_k) based on the branch:

- **Mixing Modifier**:

$$m = \begin{cases} 1.0 & \text{(main channel)} \\ s_{d1} = 0.8 & \text{(branch 1, reduced mixing)} \\ s_{d2} = 1.2 & \text{(branch 2, enhanced mixing)} \end{cases} \tag{2}$$

- **Turbulent Viscosity**: $\nu_T \leftarrow \nu_T \cdot m$
- **TKE Production**:

$$P_k \leftarrow P_k + \nu_T \cdot \text{Shear}_k^2 \cdot m \cdot \frac{u_t \cdot s_t}{\max(0.01, |u_t|)} \tag{3}$$

  where u_t is the tidal velocity, $s_t = s_{t1}$ or s_{t2} for branches 1 and 2, respectively, and $P_k \in [0, 10^{-3}]$ m^2/s^3.

Tidal Velocity Adjustment

The `AdjustTidalVelocity` method scales the tidal velocity at branch ends:

$$u_t' = \begin{cases} u_t \cdot s_{t1} & \text{(branch 1, cell } i = n_{\text{main}} + n_{\text{branch}} - 1) \\ u_t \cdot s_{t2} & \text{(branch 2, cell } i = n_{\text{main}} + 2 \cdot n_{\text{branch}} - 1) \\ u_t & \text{(main channel)} \end{cases} \tag{4}$$

Physical and Mathematical Models

The `BifurcatedEstuaryModels` class employs the following models:

- **Grid Geometry**:

$$x_i = i\Delta x + \text{rand} \cdot 0.5\Delta x \tag{5}$$

$$h_i = \left(5.0 + 5.0 \sin\left(\frac{\pi x_i}{L}\right)\right) \cdot s_d, \quad s_d = \begin{cases} 1.0 & \text{(main channel)} \\ s_{d1} & \text{(branch 1)} \\ s_{d2} & \text{(branch 2)} \end{cases} \tag{6}$$

$$A_i = \Delta x \cdot 100 \cdot (0.8 + \text{rand} \cdot 0.4) \tag{7}$$

- **Turbulent Viscosity Adjustment**:

$$\nu_T \leftarrow \nu_T \cdot m, \quad m = \begin{cases} 1.0 & \text{(main channel)} \\ 0.8 & \text{(branch 1)} \\ 1.2 & \text{(branch 2)} \end{cases} \tag{8}$$

- **TKE Production Adjustment**:

$$P_k \leftarrow P_k + \nu_T \cdot \text{Shear}_k^2 \cdot m \cdot \frac{u_t \cdot s_t}{\max(0.01, |u_t|)}, \quad P_k \in [0, 10^{-3}] \tag{9}$$

- **Tidal Velocity Scaling**:

$$u_t' = u_t \cdot s_t, \quad s_t = \begin{cases} 0.7 & \text{(branch 1)} \\ 1.3 & \text{(branch 2)} \\ 1.0 & \text{(main channel)} \end{cases} \tag{10}$$

These models capture the geometric and dynamic variations in a bifurcated estuary, enabling realistic simulation of tidal and mixing processes in distinct channels.