Article

Applications of Forward Stratigraphic Modelling in Modern Siliciclastic Settings: A Case Study from the Fraser River Delta, Canada

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Abstract: Forward stratigraphic modelling (FSM) is a relatively new approach that is used to test the importance of parameters that control stratigraphic stacking patterns and to reveal uncertainties such as sedimentation rate and accommodation space. Although FSM is commonly employed in the study of ancient systems, it is rarely applied to modern settings. The Fraser River Delta in Canada provides an opportunity to test applications of FSM in recently deposited sediments in an active sedimentary basin. Because it is un-dammed, the river enables comparison of the modern and ancient systems. It is also a well-studied river system, with sufficient data to generate a realistic model for predicting future scenarios. In this study, Dionisos software is used, and the evolution of the delta over the past 10,000 years is successfully simulated in two steps (5000 years each) using both realistic and real-time data. The main controlling parameters are observed to be the sediment supply and water discharge values, and to a lesser extent, sea level variation. Several possible future scenarios are tested, changing the main parameters to understand and to predict future morphological changes and stacking patterns. Increasing the main parameter values resulted in progradation, while reducing resulted in erosion, particularly in the subaqueous section of the delta. The results of this study can be used to calibrate numerical modelling applications in both modern and ancient deltaic settings.

Keywords: forward stratigraphic modeling; Fraser River Delta; Dionisos

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1. Introduction

Forward stratigraphic modelling (FSM) is a powerful tool to predict reservoir potential in sedimentary basins, including continental, marine, siliciclastic, and carbonate systems. Its applications have been reported to be critical for petroleum exploration, e.g., [1–3]. FSM is also an important approach to reveal uncertainties in depositional settings, such as sedimentation rate, water discharge, and sea level fluctuations, which are difficult to determine with conventional research techniques [4,5]. Consequently, FSM is becoming a regular multi-purpose approach to modeling petroleum reservoirs and has been applied commonly in ancient sedimentary basins, particularly in shallow water systems [4–8]. However, it has rarely been applied in modern siliciclastic settings (see exceptions: [9]). Given that this numerical modelling technique has a forward application in stratigraphic architecture, in this study its application is examined in a well-studied modern deltaic system (i.e., the Fraser River Delta, Canada), and its potential applications to predict future stratigraphic architecture (e.g., coastline morphological changes) are tested. These potential applications may help to prevent and better manage natural geo-hazards, such as slope failures, erosion, and subsidence. FSM has the potential to support multiple forms of multidisciplinary research.

The Fraser Delta provides an opportunity to test applications of FSM due to its limited anthropogenic modifications (limited to river dykes in the last several decades) and well-studied nature. This study tests (1) whether FSM can be applicable to modern studies, (2) what parameters are the main controlling factors (e.g., water discharge, grain size, etc.)

in reconstructing modern environments, and (3) whether FSM can be utilized to predict future changes in modern deltaic environments.

2. Study Area

The Fraser River Delta is situated along the Pacific coast of Canada (Figure 1). It is the largest river in western Canada, and it has been prograding into the Strait of Georgia (SoG), a forearc basin, for about 10,000 years, following the end of the last glaciation [10–12]. This modern delta sits on top of Pleistocene marine- and glacial-origin sand, silt, and, to a lesser extent, gravel deposits [10]. Due to its undammed nature, the Fraser River Delta represents a natural river system, with the exception of some relatively recent modifications along its river (e.g., replacement of dykes).

Figure 1. (A) Schematic map of the Fraser River Delta. The gray scale is the multibeam-derived bathymetric map provided by the Geological Survey of Canada, Pacific Division (contour interval: 50 m). (B) Three-dimensional block diagram of the Fraser River Delta. The yellow line represents low-tide sea level.

The Fraser River has a dynamic nature, with significant long-term and short-term changes in river discharge, resulting in variations in its progradation rate over time [13]. Between 10,000 BP and 5000 BP, the delta prograded approximately 13 km from the river

mouth, and another ~9 km in the last 5000 years, based on terrestrial organic matter distribution, radiocarbon age dating, and marine shell distribution collected from bore hole data [13–15]. The river discharge also dramatically fluctuates. The mean river discharge rate is approximately 3400 m³/s, while minimum discharge is 1000 m³/s and maximum discharge can reach 15,200 m³/s during snowmelt-induced freshet [16–18]. Fluctuations in the river discharge also result in variations in transported sediment load. The river annually transports about 17 million tonnes/year of sediment. Under ambient conditions, the river predominantly transports mud-size particles (i.e., silt and clay) into the SoG, while during the freshet, half of this material is sand-sized [19,20].

The SoG is a restricted basin, with complex hydrodynamic processes transporting sediments. These processes include tidal currents, waves, and deep-water renewals [17,21–23]. Waves are the dominant processes in the upper 10–15 m of the water column [17]. Once the river flow enters into the SoG, suspended sediments are either transported offshore via the river's jet plume (during freshet), or waves transport sediments southward due to the dominant strong wind direction [24], where the sediment settles in the southern parts of the SoG. In the deeper parts of the SoG (>15 m depth), tidal processes dominate along with deep-water renewals as a subordinate process. Both processes cause net northward sediment transport on and across the delta front and prodelta [21,23,25,26].

3. Dataset and Methodology

In order to create a realistic model for the Fraser River Delta and its evolution, the 3D forward stratigraphic modelling software Dionisos© from IFP (Institut Français du Pétrole) was used. This software can handle complex basinal architectures and considers a large number of input parameters (Table 1), using diffusion laws and long-term basinal scale sediment transport equations [7,27,28]. Defining diffusion coefficients can be challenging; thus, testing documented values from similar basins is a common approach, e.g., [29]. The Fraser River represents a forearc region [10]; therefore, both the marine and continental diffusion coefficients (Table 1) used in this study are tested and adopted from other studies in similar basins, e.g., [28]. These coefficient values are reasonable, since a realistic model is achieved using other input parameters that are close to today's real-time values.

3.1. Input Parameters

The spatial extent of the model was created based on the distribution of modern sediments, known evolution history of the delta, and other available datasets, e.g., [15,22,30–32]. The simulation covers a rectangular area of 40 × 60 km², with a grid size of 0.5 × 0.5 km (Table 1). The last 10,000 years is covered in two steps (step 1: 10,000–5000 and step 2: 5000–today) and one additional step (step 3) to test the next 5000 years. In other words, each step was 5000 years.

3.1.1. Initial Bathymetry

Generating an initial paleobathymetric map is the most critical step in forward stratigraphic modelling, as it controls the overall accommodation space and the geometry of stratigraphic units. It is also one of the most difficult input parameters to simulate, due to the presence of compaction, tectonic evolution, subsidence, and erosion in basins. It is particularly challenging in ancient systems, although in modern environments, defining paleobathymetry can be easier, as more data are typically available, such as the thickness of modern sediments and geophysical surveys. In addition, the effects of burial by the overlying units can be ignored. In the Fraser River Delta, the thickness of modern deltaic sediments is used, e.g., [33,34], to generate a realistic initial bathymetry. Based on these data, the bathymetry profile resembles an overall fjord-like basin, where the main depo-center is a concave, bowl-shape basin (Figure 2). It should be noted that the model does not extend further south due to limited data availability. In this model, subsidence is neglected, although some minor anthropogenic subsidence has been reported in the delta plain [33].

Table 1. Parameters used in modeling.

Input Parameter		Value			
Domain length (x-axis) (km)		60			
Domain length (y-axis) (km)		40			
Grid size (km)		0.5×0.5			
Time steps (yrs)		5000			
Sediment supply (km^3/Ma)		$10,000^{s1}; 9000^{s2}; 9000^{s3}$			
River discharge (m^3/s)		$6000^{s1}; 4500^{s2}; 4500^{s3}$			
Coarse sand (%)		$5^{s1}; 5^{s2}; 5^{s3}$			
Sand (%)		$20^{s1}; 20^{s2}; 20^{s3}$			
Silt (%)		$45^{s1}; 45^{s2}; 45^{s3}$			
Clay (%)		$30^{s1}; 30^{s2}; 30^{s3}$			
Sediment transport parameters (km^2/ky)					
		Coarse sand	Sand	Silt	Clay
K_{gravity}	Continental	20	40	60	80
	Marine	0.008	0.0110	0.0150	0.02
K_{water}	Continental	25	50	75	100
	Marine	2	4	5	6
K_{hest}	Continental	25	45	65	85
	Marine	0.01	0.02	0.022	0.024

K_{gravity} : gravity-driven diffusion coefficient; K_{water} : water-driven diffusion coefficient; K_{hest} : high-energy short-term transport. ^{s1-s3}: Steps 1–3.

Figure 2. Initial bathymetric model characterizing the Fraser Valley before the delta progradation. The main depo-center is the “fjord-like” basin. This model was created using the thickness of modern sediments e.g., [33,34].

3.1.2. Sea Level Variation

The Fraser River Valley and its surrounding area have experienced significant sea level variations, in particular, close to the end of the last glaciation period [35,36]. At around 15,000 BP, the Fraser Valley was covered by ~1.5 km thick glaciers [35]. Glacial retreat resulted in approximately 150 m relative sea level increase at around 14,000 BP. Between 14,000 and 10,000 BP, the relative sea level rapidly dropped to about 12 m below its present level, due to isostatic rebound [36,37]. The delta deposition started approximately 10,000 years BP (within the modelling interval herein). Sea level variation since the delta progradation initiated has received some attention, and there are various opinions. Several studies suggest that during delta progradation, relative sea level increased a noticeable 12 m until 2000 BP, when the relative sea level reached its current level [3,13,38,39]. Other studies indicate that sea level fluctuations were reported to be minor (~1 m) [37]. Therefore, in this study, two main scenarios are considered: (1) a 12 m increase between 10,000 and 2000 BP, and (2) a constant (zero) sea level throughout the modern Fraser River Delta evolution (step 1–2). Some recent studies also suggest that relative sea level might increase up to 2 m in the next 100 years, mainly due to anthropogenic effects [33,40]. The potential results of this relative sea level increase are also tested in this study.

3.1.3. Sediment Supply and Water Discharge

Sediment supply and water discharge values are important input parameters in forward stratigraphic modelling, as they transport sediments and fill up the given accommodation space in siliciclastic settings. The majority of modelling studies use today's reported world river values [18,41] to achieve realistic results in ancient settings, e.g., [28,42,43]. This approach is useful in ancient settings; however, real-time Fraser River discharge and sediment supply values are used in this study, as well as river location and width.

In the model, river discharge values vary between 4500 m³/s and 6000 m³/s (Table 1). These values are slightly higher than today's average values, mainly because the reported values represent recent real-time data and do not consider the fact that the discharge rate was most likely higher in the past due to the extensive glacial melting, particularly close to the early stages of the delta progradation. Nevertheless, these values are lower than today's maximum discharge rate.

Although annual river discharge values are known, it is also important to consider long-term variations along the river systems. In the Fraser River, extreme flooding events take place every 500 years [44]. The last extreme flood was reported in 1894 [45]. Thus, in the model, short-term high-energy floods (HEST) are applied to represent extreme floods [46].

3.1.4. Sediment Transport Parameters

Dionisos is based on diffusion process that is controlled by several parameters, including diffusion coefficient, water discharge, and slope [4,7,47,48]. Among these, the diffusion coefficient is perhaps the most challenging parameter to determine, as it is calculated based on variants that are difficult to quantify, such as grain shape and size, and accommodation space [48]. The diffusion coefficients used in this model are similar to other models and are listed in Table 1 [4,28,48,49].

4. Results

Evolution of the Fraser River Delta is simulated using two 5000 year time spans (Figure 3). The model shows today's delta evolution in two steps (Figure 3A–L) and provides an additional third step representing the hypothetical evolution over 5000 years into the future, assuming continuous natural conditions (e.g., without anthropogenic effects) (Figure 3M–R).

Figure 3. Simulation results demonstrating the delta characteristics and its evolution in three time steps (S1–S3). (A–F) Modelling results between 10,000 BP and 5000 BP (S1). (G–L) Modelling results between 5000 BP and present day (S2). (M–R) Modelling results of a hypothetical test run, representing the delta’s future evolution, considering no changes in the input parameters for the next 5000 years.

4.1. Step 1 (10,000 BP to 5000 BP)

In the first step (S1), the model is created using sediment supply and water discharge values that are slightly higher than those of today’s values (Table 1). Sediments fill up almost half of the fjord-like basin (Figure 3A,B). The delta plain shows approximately 15 km progradation in the southeast direction (Figure 3A). At the end of S1, water discharge shows two main flow paths: one flowing west and one flowing south (Figure 3C). The sedimentation rate shows a significant increase in the southern delta front and delta plain, and to a lesser extent, in the northern delta front (Figure 3B).

Overall grain size distribution changes significantly from the upper delta plain to the prodelta (Figure 3D–F). The upper delta plain is dominated by sandy deposits, while the

lower delta plain and the delta front are dominated by silty deposits (Figure 3D–F). The middle delta plain shows locally sand-rich and shale-rich patchy sediment distribution (Figure 3D), while the prodelta is mainly dominated by shale-rich units (Figure 3F). Very little sediment exceeds the fjord-like basin and deposit in the offshore (i.e., Strait of Georgia).

4.2. Step 2 (5000 BP to Present Day)

The second step (S2) successfully modeled today's delta morphology using sediment supply and water discharge values that are similar to present-day values (Table 1). In S2, sediments filled up the entire fjord-like basin and partially filled the Strait of Georgia (Figure 3G,H). Overall delta plain progradation reached about 24 km from the river mouth (Figure 3G). The model shows a major westward progradation during S2, but southward progradation is also noticeable (east of Point Roberts, Figure 3H). Water discharge, on the other hand, converged between Vancouver highland and Point Roberts, and bifurcated into two channels: a central channel (similar to today's Main Channel) and a south channel, situated close to Point Roberts (Figure 3I). Due to the complexity in sedimentation rate and grain size distribution, the west progradation is divided into two: the north delta and south delta, separated by the central channel. The south progradation (east of the Point Roberts) is also named the Boundary Bay delta (Figure 1). The overall sedimentation rate trend is at the delta front-delta plain boundary, with a slight increase at the south delta (Figure 3H).

The grain size distribution shows a uniform pattern throughout the delta plain and delta front during S2 (Figure 3J–L), particularly in silt percentage (Figure 3K). Sand and shale percentages, on the other hand, show a slight variation in the south delta (Figure 3J,L). When the grain size distribution in the delta front and delta plain is compared, the south delta front and delta plain represent slightly less sand content and more shale content (Figure 3J–L). The prodelta shows a pronounced increased in shale content (Figure 3L).

4.3. Simulation Step 3 (5000 Years from Present)

Step 3 (S3) represents a future scenario, presuming that all the parameters in step 2 continue operating without any modification, including sediment supply and water discharge (Table 1). Some dramatic changes are observed in the orientation of the delta progradation in S3. Delta progradation is recorded to display a shift from west to south direction (Figure 3M,N). Westward progradation was limited to 2–3 km, while southern progradation (Boundary Bay) exceeded the domain limits (Figure 3N) and overflowed towards the west after filling Boundary Bay. The water flow clearly shows that the main direction of the flow also shifted towards the south (Figure 3O). Consequently, sedimentation was mainly concentrated in the Boundary Bay delta (Figure 3N).

In S3, the delta plain is overwhelmingly represented by sandy sediments (Figure 3P). The Boundary Bay delta, where major sedimentation occurs, is dominated by shale and silt deposits (Figure 3O–R). Based on the model, shale-rich sediments are trapped in the Boundary Bay delta, while sandy and silty sediments overflow into the western basin (Figure 3P–R).

4.4. Facies Model

Utilizing grain size distribution and water depth, a facies distribution model is created along and across the Fraser River Delta, covering all simulated steps (Figure 4 and Table 2). In the delta plain (above zero sea level), the percentage of sand distribution is selected as the main facies controlling grain size, due to the overall sandy nature of the modern delta. Shale-rich zones are defined as having less than 20% sand, while sandy zones are defined as more than 25% sand (Table 2). In the subaqueous portion, the boundary between the delta front and prodelta is selected as 150 m, to simulate the real delta boundary [22]. Sand percentage progressively reduces from the delta plain to the prodelta; thus, 20% sand is selected to differentiate facies in the delta front, and 15% sand in the prodelta (Table 2).

Figure 4. (A–C) Spatial facies distribution plots at the end of each time step, interpreted based on grain size percentage and bathymetric data (Table 2).

Table 2. Grain size and bathymetric parameters utilized to interpret facies distribution.

Facies	Bathymetry (m)		Sand (%)		Shale (%)	
	Min.	Max.	Min.	Max.	Min.	Max.
Sandy delta plain	−164	0	25	38.2	-	-
Silty delta plain	−164	0	20	25	-	-
Shale-rich delta plain	−164	0	0	20	-	-
Sandy delta front	0	150	20	-	-	-
Shaley delta front	0	150	0	20	-	-
Silty prodelta	150	400	15	36.6	0	50
Prodelta shale	150	400	-	-	50	74.7

The results show that in S1 the upper delta plain is represented by sandy deposits, while the middle and lower delta plain is predominantly silty deposits (Figure 4A). The delta front shows almost uniform shale-rich deposits, and the prodelta is dominated by silt- and shale-rich deposits (Figure 4A). S2 shows a significant change, especially in the delta plain (Figure 4B). The upper and middle delta plain show sand-dominated deposits, while the lower delta plain shows silty deposits and, to a lesser extent, shale-rich deposits (Figure 4B). The vast majority of the delta front is characterized by shale-rich deposits, but local sand-rich deposits are present in the northern delta front (close to Vancouver) and the Boundary Bay delta (Figure 4B). The prodelta is represented by shale-rich deposits in both the Strait of Georgia and Boundary Bay delta (Figure 4B). S3 allows us to predict possible changes in facies distribution in the future. S3 shows that in 5000 years, the majority of the delta plain will be sand-rich, with local silty deposits at the edge of today's delta plain-delta front boundary and at the Boundary Bay delta (Figure 4C). Similarly, the delta front will also be dominated by sand-rich deposits. The distal portion of the delta front will be shale-rich (Figure 4C). The prodelta in S3 will remain shale-rich, but a local silt-rich deposition will develop in the south delta front (close to Point Roberts) (Figure 4C). Boundary Bay seems to be filled with shale-rich deposits; however, it is clear that these sediments would be

dispersed southward if the outer edge of the model was bigger. Therefore, the subaqueous Boundary Bay delta deposition is ignored in S3. Unfortunately, accurate paleobathymetric data covering the south of Boundary Bay is not available to extend the model southward.

4.5. Testing Possible Future Variations in the Fraser River Delta

Perhaps one of the most exciting capacities of forward stratigraphic modelling applications in modern environments is to test and predict changes in future morphological and stratigraphic architecture. In this study, a future model in one step (S3) is created by presuming no changes in today's input variations (Figure 3M–S). Then, we also test how the delta can evolve if sediment supply and water discharge values change over time. In this test, sand distribution maps were plotted to represent the evolution of the delta (Figure 5). Erosion maps were also plotted and compared to visualize under which conditions the delta might become unstable (Figure 6). The results of these tests show that if the sediment supply gradually increases while the water discharge gradually decreases, the majority of the sediments will not reach offshore and will be trapped at the river mouth, creating a bulge inland (Figure 5). In this scenario, only a slight erosion is observed in the distal parts of the prodelta (Figure 6). In contrast, when sediment supply gradually decreases while water discharge increases, delta progradation slows significantly, and local or regional erosion takes place (Figure 6). Erosion first starts in the upper delta plain and gradually affects the entire delta as the discharge rate increase and sediment supply decrease (Figure 6). Erosion results in exposure of underlying sand-rich delta plain and delta front deposits (Figure 5). When both sediment supply and water discharge increase, the delta shows progradation in all directions offshore, with little or no erosion (Figures 5 and 6). In this scenario, erosion occurs when discharge is more than $6750 \text{ m}^3/\text{s}$ and sediment supply is less than $13,500 \text{ km}^3/\text{Ma}$ (Figure 6). These results can play a critical role when further modifications on the river (such as placing a dam) are considered.

In addition to variations in sediment supply and water discharge, a possible sea level variation is also tested in this study. The effect of sea level variations in coastal areas is a global issue due to several reasons, such as global warming and anthropogenic influence. The Fraser River Delta may also face this issue, due to the fact that parts of the delta plain show noticeable subsidence, possibly resulting in a 2 m increase in the next 100 years [33,40]. In Dionisos software, testing variations over 100 years is not possible; however, if one considers that this relative sea level increase will remain constant in the next modelling time step, it is possible to test how stratigraphic architecture can respond to such variation. Therefore, a 100 m relative sea level increase is tested, maintaining all other parameters similar to step 2 (Figure 7). The results show a dramatic shift in the evolution of the delta: from an overall prograding system to a retrograding system (Figure 7). Sediments during this scenario deposit mostly on the Boundary Bay area, but a clear backstepping deposition is also visible on the delta plain (Figure 7). The majority of the sand accumulates on the upper delta plain (Figure 7A), while silty deposits show uniform distribution throughout the delta (Figure 7B) and shale unit deposits predominate the prodelta (Figure 7C). Water discharge shows a southward deflection towards Boundary Bay (Figure 7D), similar to step 3. No negative effect in terms of delta stability (e.g., major erosion) is observed, but it cannot be ruled out that if this scenario takes place wave erosion can be a major concern on the delta plain, resulting in a wave ravinement-like surface.

Figure 5. Hypothetical delta evolution in the next 5000 years with variant sediment supply and water discharge values. Please note that the block diagram in the center (S3) represents no changes in sediment supply and water discharge values (similar parameters used in S2).

Figure 6. Results showing erosion rate (m/MA) maps in the next 5000 years with variant sediment supply and water discharge values.

Figure 7. (A–D) Modelling results representing the effects of a hypothetical 100 m relative sea level increase in the next 5000 years. It should be noted that in this model, only the sea level curve was introduced to the model; other parameters remain similar to step 2 (Figure 3G–L and Table 1).

5. Discussion

The simulated Fraser River Delta, particularly its evolution and progradation rate, is similar to what has been documented in the literature, e.g., [10,50] suggesting that the majority of the input parameters used in this study were predicted accurately. Diffusion coefficients adopted from other studies were documented to work correctly, because other input parameters used in this study are real-time or close to real values. Although each parameter played a critical role in the model, sediment supply and water discharge values were the main controlling mechanisms. Today's known values and available data (e.g., paleobathymetry, river discharge, and sediment supply) were enough to successfully simulate the overall stratigraphic architecture, shoreline morphology, and delta progradation, particularly in S2 (Figure 3G–L). However, some parameters were modified in S1, considering changes in paleodepositional conditions.

Today's sediment supply and water discharge values were observed to be too low to replicate the progradation of the delta in the first 5000 years to fill up the accommodation space (Table 1 and Figure 3A,B). Following several attempts, it was realized that the river discharge and sediment supply values during S1 must have been slightly higher than today's values (Table 1). Given that the Fraser River Delta is a post-glacial setting, the higher values suggest rapid melting of glaciers, increasing both sediment supply and water discharge. Similar variations have been documented in other deltas located in high latitude areas, e.g., [51]. Today, the Fraser Delta experiences similar yearly low and high sediment supply and water discharge values in winter and summer, respectively. During the summer

season, both values are significantly higher due to melting of accumulated snow, while they are lower when snow accumulates in highland areas [32,52].

The two sea-level variation scenarios displayed dramatic differences in delta progradation. A constant sea level (zero fluctuation) successfully created the delta progradation up to its today's limits. However, a 12 m sea level increase failed to generate a realistic model. When a 12 m sea level increase was used, sediments were trapped in the delta plain region, and delta progradation stopped short of today's delta limits, despite countless attempts to change and test variations in parameters (e.g., sediment supply and diffusion coefficients). Although this observation may suggest that the Fraser Delta has not experienced major sea level fluctuations, it should be noted that there are other parameters that may have contributed to delta progradation. For example, the net northward sediment transportation due to strong tidal currents [21,25] or deep-water renewal events, bringing external sediments into the Fraser basin [23], may have played a role in supplying additional sediments to the delta. If these processes were sufficient, the delta progradation could reach to its current limits under a 12 m sea level increase. Unfortunately, testing these processes is beyond the current capacity of the software.

Perhaps one of the most important parameters to validate the delta evolution between a real system and a modelled system is the progradation rate. The Fraser River Delta's progradation rate has previously been documented, based on the sedimentological record [11,13,15,50]. The model successfully created a similar progradation rate in two steps (Figure 3). The simulated first and second steps displayed 15 km and 9 km (cumulative: ~24 km) progradation, respectively (Figure 3).

Water discharge data show pathways for major channels. In the Fraser River Delta, the location of the main distributary channel is unknown at 5000 BP, but it has been suggested that the river system was at one point flowing east of Point Roberts (towards the Boundary Bay delta) before shifting toward the Strait of Georgia, as in today [10,17]. The model displays one major and one subordinate river system at the end of S1 (Figure 3C). The major system flows towards the west (similar to present day), while the subordinate one flows south, into the Boundary Bay delta. The major system shows the highest water discharge values, suggesting that this might be the main distributary channel at 5000 BP, but the smaller system also suggests that the main channel might have shifted frequently. Increased sedimentation rate at the Boundary Bay delta during S1 (Figure 3B) shows that majority of the sediments were deposited in Boundary Bay. This may suggest that distributary channels predominantly flowed towards Boundary Bay at early stages of the delta progradation, which is concordant with previous estimations, e.g., [10,17]. In the present day, the Fraser River has one main distributary channel (Main Channel; Figure 1) and a few subordinate channels. Recent channel locations and migration pathways have been well documented [53]. The main channel of the Fraser River shows frequent shifts between the south of today's main channel and the north of Point Roberts (south delta plain) in the early to late 1800s, until it was controlled by placing dykes in 1912 [15]. These frequent shifts in the main channel have been linked to downstream migrating bars obstructing channels and resulting in water flowing into other channels [54]. Although such small-scale bar formations are beyond the resolution of Dionisos software, the model successfully simulated overall channel systems (Figure 3I). This suggests that the main water flow pathways can also be closely predicted using forward stratigraphic modelling at the end of each time step.

The test results for step 3 show a dramatic shift in the main channel direction from the westward flowing to southward (into Boundary Bay) flowing pathway (Figure 3O). This indicates that under natural conditions, the river could be shifted towards the Boundary Bay delta within the next 5000 years. Although the model does not show a major erosion in today's delta plain and delta front, it should be noted that tides and waves are reported to cause local erosion in the south of today's delta front, and they still have the potential to create major stability issues [21].

Comparison of grain size variation and facies changes in the Fraser River Delta is complicated due to the dynamic nature of the river, resulting in frequent variations in depositional environments throughout the delta, e.g., [30,55,56]. The model also shows that grain size and facies distribution vary significantly in space and time (Figures 3 and 4). Although overall facies and grain size architectures show similarities with published studies, and the delta shows a clear coarsening upward succession, finer resolution facies maps to correlate or calibrate it with the real-time data could not be achieved due to the limitations in the resolution of the modelling software. Moreover, hydrodynamic conditions in the SoG are controlled by tides and deep-water currents [17,23,57], which are beyond the capacity of the Dionisos.

6. Conclusions

Forward stratigraphic modelling is applied to the modern Fraser River Delta, Canada, using Dionisos software. The results document that modern siliciclastic systems can be simulated using real-time input parameters and can help predict future geomorphological changes and stratigraphic architectures. In this study, the Fraser River Delta is successfully created in two time steps and in one further step for its future architecture. The delta evolution and how it can change with variations in sediment supply and water discharge values are documented. The possible effects of a hypothetical 100 m relative sea level increase in the delta evolution are also illustrated. The results document that forward stratigraphic modelling is applicable for relatively short (5000 years) time steps; therefore, it can be used in modern systems (e.g., developed following the last glaciation).

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