Coastal processes and sedimentary facies in the Zohreh River Delta (Northern Persian Gulf)

Mohammadreza Gharibreza a,*, Alireza Habibi a, Sayed Reza Imamjomeh a, Muhammad Aqeel Ashraf b

a Department of River Engineering and Coastal Protection, Soil Conservation and Watershed Management Research Institute, Tehran, Iran
b Department of Geology, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form 10 June 2014
Accepted 19 June 2014
Available online xxxx

Keywords:
Zohreh River
Erosion
Sedimentary facies
Sedimentation
Tidal currents
Delta progradation

ABSTRACT

The Zohreh River Delta is one of the largest deltaic plains along the northern coast of the Persian Gulf. This delta is located near an international navigation corridor, which is affected by long-term delta progradation. Therefore, the research objectives of this study were to determine the coastal sedimentary processes of the Zohreh River Delta and to detect the evolutionary trend of the deltaic plain at the northern Persian Gulf. The research method was formulated to achieve objectives herein, including field measurements, numerical modeling, remote sensing and laboratory analyses. The results showed that flash floods and turbidity currents transport sediment to the deltaic area, and tidal currents play an important role in sediment redistribution and in the high diversity of sedimentary facies. Flood plains, tidal flats, crevasse splays, nebka, and sabkha are the most important sedimentary facies in the study area. Gypsum and salt crystal are frequently grown in supratidal and intertidal zones because of a dominantly arid climate. The river and tidal currents are responsible for an annual sediment transport of 321,310 m³, while the sediment transport by littoral drift is calculated to be 81,000 m³ annually. MIKE-21 (a coastal modeling software) revealed that 80% of the sediment is transferred into the subtidal zone and the remaining 20% is deposited at the river mouth. Applications of GIS tools showed that the mean annual sedimentation rate at the river mouth and the long-term shoaling rate have been 0.07 m and 2.45 m, respectively. The rate of long-term progradation of the delta implies an increase of sediment supply from the catchment area due to land use changes and river bank erosion. A key part of this research is presenting the implications of the permanent shoaling trend which is prograding toward the international shipping corridor at the north of the Persian Gulf.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

The Persian Gulf is one of the most important basins around the world and is well known for its geological, commercial, navigational and geopolitical aspects. The regional importance of the north of the Persian Gulf has been highlighted by several scientists and recent politicians. For instance, Arnold Wilson (1888–1955), who was the colonial administrator of Mesopotamia (Iraq) during and after the First World War, believed that no water channel has been so significant as the Persian Gulf to geologists, archeologists, geographers, merchants, politicians, excursionists, and scholars in the past or even at present. This water channel which separates the Iran Plateau from the Arabian Plate has become an Iranian Identity since at least 2200 years ago (UNGEGN, 2006).

The Zohreh River Delta is adjacent to an international corridor of navigation at the north of the Persian Gulf. The progradation and morphological changes of this delta showed that the migration of this body of land toward the navigation corridor is permanent. The most important gaps in knowledge were the rate of shoaling and land progradation, coastal and deltaic processes that contributed to the evolutionary trend of the Hendijan Delta. Deltas are important coastal sedimentary environments and reflect the general geological setting, climate, river hydrology and hydrodynamic conditions of the surrounding environment. Deltaic landforms, such as paleoshorelines are indicative of paleoclimate, the ancient geography of the deltaic plain, tectonics and eustatic sea level changes. Furthermore, evidence of late-Holocene human activity has been observed on delta plains worldwide (Gharibreza et al., 2008; Leeder, 1999; Pye, 1994; Reading, 1986; Reijers, 2011). Therefore, evolutionary trend of the coastal area of the Persian Gulf since the late-quaternary has been studied by Falcon (1947), Vita-Finzi (1979), Lambeck (1996), Reyss et al. (1998) and Gharibreza et al. (2008). These studies have reconstructed the sedimentary basin during the late Quaternary using the 14C dating method. Previous studies (Falcon, 1947; Vita-Finzi, 1980; Reyss et al., 1998) have highlighted the effects of tectonics along Iran’s coast since the Last Glacial Maximum (LGM), the end of which began 18,000 BP. Since then, the coastal processes and the evolution of the deltaic plains, particularly along the northern Persian Gulf, have been controlled by eustatic and tectonic factors. Complementary methods, such as application
of remote sensing and comprehensive sediment sampling, are the recommended methods for mapping the geomorphic and sedimentary facies of recent coastal environments (Boyd et al., 1992; Dalrymple and Choi, 2007; Dalrymple et al., 1992; Heap et al., 2004; Nichol, 1991). For example, Heap et al. (2004) mapped the sedimentary facies of several wave and tide-dominated estuaries and deltas in Australia by visually inspecting aerial photographs, Landsat TM images and topographic maps. A literature review has revealed that the evolutionary trend of the northern Persian Gulf has been drawn by Gharibreza et al. (2008) and Heyvaert and Baeteman (2007) needs to be verified and checked by investigating current coastal sedimentary processes. Therefore, a study of sedimentary facies, the hydrology of the Zohreh River and the hydrodynamics of wave-induced and tidal currents were recognized to verify previous studies and reveal contributors in the evolution of the Hendijan Delta. The research hypothesis is that long-term trends of deltaic evolution will be revealed by investigating current coastal processes. Therefore, the study's primary objectives were to determine the sedimentary processes and identify facies present in the Zohreh River Delta. Additionally, this study aimed to determine the relative contributions of various mechanisms contributing to erosion and sedimentation in the study area. Accordingly, the research method was formulated to carry out the comprehensive field observation and to run numerical models (Mike 21) and to use geographic information system (GIS) in order to investigate deltaic processes which are involved in the evolution of the Hendijan Delta.

1.1. Study area

The Zohreh River Delta (Hendijan Delta) is an active, morphodynamic area located in southwestern Iran and the northern Persian Gulf, between 29°59′–30°15′ and 49°25′–49°50′. It is a river-dominated delta that has developed into the Persian Gulf in a southwesterly direction. The river catchment area is 16,033 km² and is divided into mountainous (10,789 km²), lowland (5244 km²) and coastal areas. The mean and annual discharge values for the Zohreh River are 87 m³ s⁻¹ and 2729 million cubic meters (MCM), respectively. Gharibreza (2005) reported the hydrodynamic characteristics of the Hendijan Delta. For the purpose of this report, the mean higher high water (MHHW), mean lower low water (MLLW) and mean sea level (MSL) of the Hendijan Delta are 2.7 m, 2.07 m, 1.3 m, 0.73 m and 1.67 m, respectively.

1.1.1. Geological setting

The Zohreh River Delta is part of the Khuzestan Plain, which has developed at the southwest of the Zagros structural zone. Lower-to-upper Miocene strata are well exposed at the Rag Seifid anticline to the northeast of the delta. The Miocene stratigraphy includes the Ghachsaran (Early Miocene), Mishan (Middle Miocene), Aghajary (Late Miocene), and Bakhtiary (Plio-Pleistocene) Formations. Overall, the slope gradient of the southern flank of the anticline is 8° to the southwest. The Quaternary sequence includes 39 m of undifferentiated fine-grained sediments and shell debris (Fig. 1). This sequence was obtained from an exploration well (Hendijan No. 6) drilled by Iran’s oil company in the center of the Zohreh River Delta. According to the glacial-hydro-eustatic model described by Lambeck (1996), the sea level was 2 to 3 m higher than its present level at 6000 BP and began to decline at 4000 BP. Therefore, the upper Quaternary sedimentary sequence of the Hendijan Delta may be composed of the following elements: (1) basal deposits composed of deltaic sediments that were deposited during the Last Glacial Maximum (18,000 BP) when the Euphrates River discharged directly into the middle of the Persian Gulf; (2) marine deposits that were deposited on the deltaic deposits since 6000 BP; (3) the accumulation of detritus and fluvial deposits on marine sediments since 4000 BP; or (4) upper Holocene and recent deltaic deposits that were deposited since 2500 BP.

2. Materials and methods

The research method is one of the key parts of this study in which geological setting, paleoshorelines, sedimentary facies, wave-induced, river and tidal currents, wave regime, shoreline changes, erosion and the sedimentation situation of a delta were studied by using field measurements, laboratory analysis, numerical modeling and the geographic information system. This method was formulated in order to achieve the objectives of the research. The authors believe that the present research method is a suitable guideline in order to investigate the evolution of the deltaic processes around the world because the evolutionary trend of a delta would be comprehensively revealed.
2.1. Sampling and sample preparation

Fourteen sediment samples were collected from the Zohreh river-bed, prodelta and delta front using a Van Veen grab sampler. Twenty-eight sediment cores were also taken from the Zohreh River and the delta plain facies using a percussion drilling set and a driven percussion hammer (Atlas Copco Cobra 248) (Fig. 2). The cores were extended to a depth of 1 m in a 3 × 3 km pattern to explore vertical sediment size variations (Fig. 3). The sediment cores were sliced into three sections based on variations in sediment size. A total of 68 samples were dried at 80–110 °C and prepared for further analysis. The samples were analyzed to determine the vertical and lateral grain size distributions using the Wentworth (1922) method. Based on this method, the sieves were sized to measure the proportions of gravel, coarse sand, medium sand, fine sand, very fine sand and particles finer than 0.063 (No. 230 mesh). A portion of the finest sediment (silt and clay) was then collected for laser analysis. A MALVERN Master Sizer was applied to analyze fine grain sized particles following the relevant separation procedures. Finally, grain size distribution plots, textural descriptions, and the calculation of statistical parameters were performed using the GRADISTAT software program, version 6.0 (Blott and Pye, 2001).

2.2. Hydrodynamics of waves and tidal currents

Waves, wave-induced currents and tidal currents were surveyed to estimate sediment transport on the Zohreh River Delta. The velocities of currents in vertical profiles (0.2D, 0.5D and 0.8D) and the directions of the tidal current at 25 stations were recorded using a Valeport BFM 308 Current Meter. Additionally, two stations recorded wave hydrodynamics using a S4 current meter. The general direction and velocity of the tidal currents were also estimated by float tracking using two superficial (0.2D) and subsurface (>0.5D) floats from 13 liberation points. The measurements of the tidal currents with these methods coincided with the spring tide, when maximum sediment transport by tidal currents was expected. In addition to tidal currents, the speeds and directions of long shore currents were surveyed during this study.

2.3. Sediment transport measurement

Fluvial and tidal currents play important roles in the transportation and redistribution of sediments in deltaic environments. An outermost
and permanent cross section of the Zohreh River was examined to record the sediment transport rate. A certain volume of suspended load during ebb and flood events was sampled using an Eijkelkamp peristaltic pump across the three sub-sections and three vertical levels (0.2D, 0.5D and 0.8D). The water sampling events coincided with the water velocity measurements at each station.

2.4. Hydrographic surveying

The hydrographic surveying was performed in the Zohreh River mouth, along the river channel and along a 5-km stretch of the delta front in accordance with the Manual of Hydrographic Operation (Stoffers and Ross, 1979). The bed morphology was recorded in a 20 × 20 m network and a scale of 1:500. The depth records were correlated to the national benchmark at the Sajjaphy fishery port, which is located approximately 5 km from the mouth of the Zohreh River.

2.5. Geographic information system (GIS)

The ArcGIS version 10.1 software package was used to develop a georeferenced digital GIS-ready data set from previously published paper-based maps, digital topographic maps and surveyed and collected real-time data. The horizontal positioning system was referenced to the WGS 1984 UTM Zone38 North projection system. The previous GIS-ready data include satellite images from LandSat taken in 2002 with spatial resolutions of 30 m, which were used to develop some of the base maps. A photo-mosaic of the study area was prepared by merging 84 geo-referenced aerial photos (taken in 1967 at a scale of 1:20,000). The georeferencing, on-screen digitizing and overlaying steps were performed using the GIS software program. River bank erosion and channel migration of the Zohreh River between 1967 and 2002 was estimated using a GIS tool. Furthermore, using this tool a map of the sedimentary facies across the Zohreh River Delta was sketched, and its accuracy was verified by field observation of relevant sedimentary features.

![Fig. 4. Distribution of sedimentary facies at the study area.](image-url)
2.6. Numerical modeling

MIKE-21 is a depth-averaged two-dimensional (2-D) numerical modeling tool which is designed by the Danish Hydraulic Institute (DHI, 2003) in order to simulate water levels and flows in rivers, estuaries, bays and coastal areas. The program can simulate both steady-state (constant) flow conditions and unsteady (varying over time) flow conditions in the two horizontal dimensions. The MIKE-21 software program was employed to model and estimate wave-induced flows in rivers, estuaries, bays and coastal areas. The information includes the bathymetric and topographic data used to create the computational grid, the refinement of the grid itself, the channel and floodplain roughness values used within the model, and the correct flow boundary conditions located at the appropriate locations throughout the model.

3. Results and discussion

The objectives of this research have been clearly achieved and the questions posed by this research have been answered by resultant data. Results showed that the hypothesis of the research has been appropriately tested by selected methods. The resultant data included deltaic sedimentary facies, a regime of different currents, sediment transport, erosion and sedimentation patterns along the Zohreh River and at the delta front, and rate of delta progradation. In addition, the reasons for the evolutionary trend of the Hendijan Delta are discussed appropriately.

3.1. Deltaic sedimentary facies

Several sedimentary facies were recognized within the study area (Fig. 4). Table 1 shows the diversity and distribution of the sedimentary facies that were interpreted based on the aerial photos from 1976. The Zohreh River channel is a corridor for transferring several types of sediments during normal and flash flood conditions. According to hydraulic sorting of sediment a decrease in the mean grain size was observed downstream of the Zohreh River channel. Results have showed that the texture of sediments has been changed at the connection points of these facies to crevasse splays, point bars, salt marshes, tidal flats and intertidal zone facies. The floodplain is the widest-spread sedimentary facies in the study area, where most of the land surrounding the river has a slope gradient of 0.001%. The average textural results for sand, silt and clay particles were 2.5 ± 1%, 73 ± 3% and 24 ± 6%, respectively. Superficial mud cracks and thin and planar lamination were the most common sedimentary structures in this facies. There was an interfingering distribution of floodplains, tidal flats, and salt marshes (sabkha). Water exchange was verified by the existence of evaporites and salt crystals, especially at a depth of 80–100 cm. Crevasse splay is usually developed at the outside edges of meanders where floods are forced onto the adjacent plains, releasing large amounts of sediment close to the river channel. These facies are distributed in a study area of 6940 ha and the widest ones have developed to the south of Hendijan City. The texture of sediments is mainly silty (Table 1) which changed to muddy at the lowest part of the splay. Clay-rich layers were observed, especially at the three depths of 0–20, 40–60 and 80–100 cm, indicating the role of periodic flash floods in the flux of coarse grains to crevasse splays. Distributary channels in crevasse splays have been responsible for the development of interbedded layers of clays with sand particles. Recognition of these channels brings advantages for land reclamation in water management planning in the study area. The meandering pattern of the Zohreh River has facilitated the development of point bars on the inner bends of the river channel. Some river terraces are located on the older point bars. Similar to other facies, silt with a frequency of 83 ± 5 is the main texture of sediment. The point bars revealed unidirectional bedforms, such as cross-bedding and planar lamination, and graded bedding. The field observations showed the ability of point bars to support a deltaic water management plan and introduced suitable places for date palm plantations. Sabkha is a well-known facies along the southern and northern Persian Gulf, in which the periods of seasonal dryness are long and the tidal flats are wide. The hot season commences in early April and continues until the end of September, when the maximum temperatures are approximately 50 °C and dry winds blow during the extended summer. The sediment column largely includes salt crystals, gypsum nodules and superficial evaporites. The Gachsaran Formation, which is composed of anhydrite and salt rock units, is a common source of the dissolved loads at the catchment area. Similar evaporites were reported by Shearman (1966) in the southern Persian Gulf sabkha plains. Gypsum is the most common precipitate within the sediments of inland sabkha, where it forms the common desert roses (Tucker, 1991). Within another inland basin in the study area, abandoned channels were recognized due to the accumulation of evaporites. These basins are suitable areas for trapping and enriching brine and saltwater, which are supplied by rivers and tidal currents. The average proportions of sand, silt and clay particles imply the silty texture of sediment. The tidal flat is the widest marine deltaic facies and occupies 21% of the study area. A 2-m tidal range dictates the wide horizontal coverage, particularly during the spring and neap tide periods. Once again, the importance of mixing of sediments

### Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Sedimentary facies</th>
<th>Area (ha)</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zohreh River channel</td>
<td>1130.3</td>
<td>1.90</td>
</tr>
<tr>
<td>2</td>
<td>Flood plains</td>
<td>20,367.7</td>
<td>34.25</td>
</tr>
<tr>
<td>3</td>
<td>Abandoned channels and Ox bow</td>
<td>186.5</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>Crevasse splay</td>
<td>6940.3</td>
<td>11.67</td>
</tr>
<tr>
<td>5</td>
<td>Point bar</td>
<td>2015.24</td>
<td>3.39</td>
</tr>
<tr>
<td>6</td>
<td>Intertidal zone</td>
<td>2080</td>
<td>3.50</td>
</tr>
<tr>
<td>7</td>
<td>Sabkha (evaporated plain)</td>
<td>5596.93</td>
<td>9.41</td>
</tr>
<tr>
<td>8</td>
<td>Tidal flat</td>
<td>12,531.2</td>
<td>21.1</td>
</tr>
<tr>
<td>9</td>
<td>Delta front and shoaling</td>
<td>801.1</td>
<td>1.35</td>
</tr>
<tr>
<td>10</td>
<td>Transverse dunes and Delta Chenier</td>
<td>1133.8</td>
<td>1.91</td>
</tr>
<tr>
<td>11</td>
<td>Sand shadows dunes</td>
<td>6487</td>
<td>10.91</td>
</tr>
<tr>
<td>12</td>
<td>Hendijan City</td>
<td>2005</td>
<td>0.34</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Sub-section</th>
<th>Depth (m)</th>
<th>Current velocity (m s⁻¹)</th>
<th>Concentration (g L⁻¹)</th>
<th>Mean velocity (m s⁻¹)</th>
<th>Area (m²)</th>
<th>Mean water discharge (m³ s⁻¹)</th>
<th>Mean concentration (g L⁻¹)</th>
<th>Mean sediment discharge (kg s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.88</td>
<td>0.8</td>
<td>0.61</td>
<td>0.71</td>
<td>158.75</td>
<td>112.71</td>
<td>0.36</td>
<td>40.57</td>
</tr>
<tr>
<td>B</td>
<td>2.2</td>
<td>0.61</td>
<td>0.27</td>
<td>0.72</td>
<td>266.61</td>
<td>191.96</td>
<td>0.19</td>
<td>36.47</td>
</tr>
<tr>
<td>C</td>
<td>0.9</td>
<td>0.95</td>
<td>0.17</td>
<td>0.2</td>
<td>200.29</td>
<td>116.17</td>
<td>0.32</td>
<td>37.17</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>625.65</td>
<td>420.84</td>
<td></td>
<td>114.21</td>
</tr>
</tbody>
</table>
between the tidal flat and floodplains was highlighted in the study area. Silt texture is also the common texture of sediments in this facies in which the mean sand, silt and clay particles were 5 ± 2%, 77 ± 5% and 18 ± 5%, respectively. The sediment sequence represents an upward decrease in grain size and an increase in the levels of evaporites and salt crystals. Herring-bone cross-bedding and bioturbation were common sedimentary structures in this facies. According to Davis and Hayes (1984), the study area is classified as a mesotidal coast wherein the tidal range is 2 m and the intertidal zone is considerably developed. The field observations demonstrated varying grain sizes in the sediments that accumulated between the shore face and the subtidal zone. The number of sand-sized grains increased 13% due to longshore current effects, whereas the clay and silt portions decreased to averages of 20% and 66%, respectively. The field observations confirmed both

<table>
<thead>
<tr>
<th>Sub-section</th>
<th>Depth (m)</th>
<th>Current velocity (m s⁻¹)</th>
<th>Concentration (g L⁻¹)</th>
<th>Mean velocity (m s⁻¹)</th>
<th>Area (m²)</th>
<th>Mean water discharge (m³ s⁻¹)</th>
<th>Mean concentration (g L⁻¹)</th>
<th>Mean sediment discharge (kg s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>0.15</td>
<td>0.54</td>
<td></td>
<td>0.24</td>
<td>158.75</td>
<td>38.1</td>
<td>0.38</td>
<td>14.48</td>
</tr>
<tr>
<td>1.5</td>
<td>0.17</td>
<td>0.08</td>
<td></td>
<td>0.24</td>
<td>158.75</td>
<td>38.1</td>
<td>0.38</td>
<td>14.48</td>
</tr>
<tr>
<td>2.4</td>
<td>0.4</td>
<td>0.54</td>
<td></td>
<td>0.24</td>
<td>158.75</td>
<td>38.1</td>
<td>0.38</td>
<td>14.48</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>0.7</td>
<td>0.09</td>
<td></td>
<td>0.24</td>
<td>260.61</td>
<td>136.29</td>
<td>0.24</td>
<td>32.71</td>
</tr>
<tr>
<td>1.75</td>
<td>0.7</td>
<td>0.33</td>
<td></td>
<td>0.71</td>
<td>260.61</td>
<td>136.29</td>
<td>0.24</td>
<td>32.71</td>
</tr>
<tr>
<td>3.2</td>
<td>0.73</td>
<td>0.29</td>
<td></td>
<td>0.71</td>
<td>260.61</td>
<td>136.29</td>
<td>0.24</td>
<td>32.71</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.59</td>
<td>0.12</td>
<td></td>
<td>0.6</td>
<td>200.29</td>
<td>120.17</td>
<td>0.11</td>
<td>13.22</td>
</tr>
<tr>
<td>1.25</td>
<td>0.64</td>
<td>0.06</td>
<td></td>
<td>0.6</td>
<td>200.29</td>
<td>120.17</td>
<td>0.11</td>
<td>13.22</td>
</tr>
<tr>
<td>2</td>
<td>0.57</td>
<td>0.15</td>
<td></td>
<td>0.6</td>
<td>200.29</td>
<td>120.17</td>
<td>0.11</td>
<td>13.22</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>625.65</td>
<td>294.56</td>
<td>60.44</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Direction and velocity of flood currents around the Zohreh River Delta.
sediment mobility and the mixing of sediments with other tidal and even floodplain facies. The tidal action was manifested in rill and gully erosion and riverbank collapses along the intertidal zone of the Zohreh River. The shoaling area correlated with the delta front and the subtidal facies at the mouth of the Zohreh River. The contribution of clay-sized particles is clearly increased to 46 ± 10%, while the silt portion is reduced to averages of 54 ± 10%. The final stage of sediment transport at deltaic plains and the calm depositional environment for the accumulation of the fine sediments is demonstrated by the muddy texture. The clear seaward progradation of the shoaling area over the intertidal zone was obtained using GIS tools.

3.2. Erosion and sedimentation along the Zohreh River channel

Evidence of medium-term (35 years) erosion and sedimentation processes has been demonstrated by some cut offs, channel migration and development of point bars along the Zohreh River. Using GIS tools, the medium-term bank erosion and sediment accumulation areas were estimated to be 538 ha and 378 ha, respectively. Thus, based on the mean thickness (2.5 m) of the riverbanks along the Zohreh River, bank erosion and deposition in the river channel occurred at rates of 385,000 m³ yr⁻¹ and 275,000 m³ yr⁻¹, respectively.

3.3. Sediment discharge from the Zohreh River

According to a medium-term data range (1973–2003), the sediment discharge of the Zohreh River was obtained 4 million m³ yr⁻¹. The Zohreh River catchment is known to have the highest sediment yield (635 ton km⁻²) among the sub-catchments in the Persian Gulf. Several erodible rock units belonging to the Aghajary and Mishan Formations release high quantities of detrital sediments. The field observations indicated that tidal currents are mainly responsible for the redistribution of sediments at the lower deltaic plain. Accordingly, the mean concentrations of the suspended loads during flood and ebb events were calculated 0.5 g L⁻¹ and 0.2 g L⁻¹, at 12 measuring stations. The quantities of sediment released during flood and ebb currents (Tables 2 and 3) were 60.44 kg s⁻¹ and 114.21 kg s⁻¹, respectively. The sediment discharge values for the bi-diurnal flood and ebb currents were calculated as 985 m³ and 1860 m³, respectively.

Fig. 6. Direction and velocity of ebb currents around the Zohreh River Delta.
3.4. Velocity and direction of tidal currents

The distribution of tidal currents at the delta front was studied using a float tracking operation (the Lagrangian method) to a maximum distance of 6 km from the beach. According to field measurements, the movement patterns of superficial and deeper currents during the ebb event have been N325 at 0.27 m s$^{-1}$ and N308 at 0.72 m s$^{-1}$, respectively. Indeed, this pattern of ebb current is part of regional currents at the northern Persian Gulf, which commenced from the Khore Mousa (Mousa Estuary). In contrast, the effects of bed morphology were apparent 5 km from the beach, where flood currents were diverted to the Zohreh River Delta. The superficial and deeper currents during the flood event were characterized by currents flowing N45 at 0.32 m s$^{-1}$ and N38 at 0.34 m s$^{-1}$, respectively. Field observation indicated a U-shaped plunge line of flood currents which is classified as a class II intrusion front on the basis of the Largier (1992) classification. The flood current speed accelerated to 0.6 ± 0.2 m s$^{-1}$ as the currents converted on the mouth of the Zohreh River. The MIKE-21 NSW module properly estimated the vectors of the ebb and flood current around the Zohreh River Delta (Figs. 5 and 6). The velocity of the flood currents ranged from 0.35 m s$^{-1}$ to 0.75 m s$^{-1}$, and it flowed toward the northwestern portion of the study area. The distribution of flood currents in the delta plain was controlled by the bed profile and the morphologies of the delta front and tidal flats. Similarly, the lowest (0.2 m s$^{-1}$) and highest (1 m s$^{-1}$) velocities of the ebb currents were recorded on the tidal flats and tidal channels (Fig. 5), respectively. Overall, the field measurements verified the MIKE-21 results with respect to the direction and velocity patterns. The Zohreh River Delta is a dynamic environment with regard to sediment transportation and distribution.

4. Discussion

The Zohreh River Delta represents characteristics of a river-dominated delta in which flash floods are responsible for the considerable volume of sediments to the deltaic plain. This study highlights the effects of the regional geological setting, neotectonics, changes in land use, river hydrology, hydrodynamic regime of waves and tidal currents, action of waves and tides on sediment redistribution, and climate conditions on delta plain evolution. The Zohreh River Delta, which is connected to a structural depression (Persian Gulf), will likely maintain a constant sedimentation regime. Variations in paleoclimate conditions caused the development of distinct paleoshorelines, which are parallel to the current coastline. A decrease in the average grain size can be attributed to hydraulic sorting, through which sand-sized particles were reduced from 46% to 2%. However, the large proportion of clay-sized particles at the delta front and mud flat areas (28% and 54%, respectively) indicates that waves did not affect sediment redistribution on the river delta. A clay-rich layer was identified at a depth of 1 m across the delta plain, indicating that a special climatic period occurred, during which time this layer was deposited from poorly sorted viscous flows, such as mud flows. The study of sediment textures revealed that silt-rich (79 ± 12%) sediment was deposited into the floodplains, river terraces, tidal flats, tidal channels and sabkhas (Fig. 7). Therefore, the cumulative curve was highly skewed toward fine to very fine for the analyzed samples. Furthermore, the relative coarsening-upward grain size in the sediment column indicates a relative increase in the sediment transport dynamics and sedimentation in recent decades. The sediment transport mechanisms were evaluated with a diagram in which sorting was plotted via skewness values (Lewise and McConchie, 1994) (Fig. 8). The turbidity and river mechanisms accounted for a majority of the sediment transport and deposition in the study area. The current conditions in southwestern Iran suggest rapid sedimentation via periodic flash floods under an arid to semi-arid climate regime. The clear development of a delta front and shoaling area (115 ha yr$^{-1}$) over approximately three and a half decades (1967–2002) suggests the contribution of additional sediment sources, such as long shore drift and the Karoon River in the northern Persian Gulf. The application of the CERC formula which is released by Wang et al. (2002) showed effects of littoral drift and wave-induced currents in sediment transport (Table 4). Southerly and southwesterly waves account for a sediment transport of 69,305 m$^{3}$ yr$^{-1}$, while westerly and northwesterly waves account for a sediment transport of 151,023 m$^{3}$ yr$^{-1}$. Therefore, a net total of 81,718 m$^{3}$ yr$^{-1}$ of sediment is transported via long shore drift toward the mouth of the Zohreh River. The field measurements revealed a sediment discharge of 321,310 m$^{3}$ yr$^{-1}$ in the tidal currents located at the river mouth. In total, sediments were supplied at a rate of 403,029 m$^{3}$ yr$^{-1}$ to the deltaic plain in the study area. In contrast, between 1967 and 2002, the delta front and shoaling area grew at a rate of 115 ha yr$^{-1}$. The MIKE-21 MT module results indicate that only 20% of sediments are contributing to the development of a shoaling area and 80% of sediments are transferring to the subtidal zone. Therefore, the latter sediments account for annual and medium-term accumulation rates of 0.07 m and 2.45 m, respectively, at the mouth of the Zohreh River. This study clearly revealed the permanent progradation.
5. Conclusions

Resultant data clearly indicated that research objectives have been achieved in this study. In addition, questions about the evolutionary trend of the Zohreh River Delta have been properly answered. A literature review showed the gap where the progradation of the deltaic plain at this part of the Persian Gulf has not been studied. Therefore, the key story of this study was a regime of delta progradation at the north of the Persian Gulf. The extension of the shoaling area toward the international corridor of shipping at the north of the Persian Gulf. The overall resultant data of this research showed an erosive regime along the Zohreh River and the depositional regime that is prominent on the tidal plains and at the delta front. The Zohreh River Delta represents a high diversity of sedimentary facies that notes the contribution of several mechanisms in the redistribution of sediments. The net river and tidal sediment discharges has been estimated at 321,310 m³ yr⁻¹, whereas 81,000 m³ yr⁻¹ has been contributed by littoral drift. The application of numerical models together with field measurement was another innovative work of this study, wherein the MT module revealed that only 20% of the sediment is contributed by littoral drift.

Acknowledgements

The research was financially supported by Grant PG008-2013B, UMRG (RG257-13AFR) and FRGS (FP038-2013B). The senior author gratefully acknowledges Dr. Ali Karami for his advice on the implementation of the research methods. The author also offers his sincerest gratitude to Dr. Ziaodin Shoaei, Dean of the Soil Conservation and Watershed Management Research Institute, for his financial support and supplementary advice.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.catena.2014.06.010. These data include Google map of the most important areas described in this article.

References


