

Beach erosion along Al Batinah coast, Sultanate of Oman

A. Y. Kwarteng¹ · S. M. Al-Hatrushi² · W. K. Illenberger³ · A. McLachlan⁴ · A. Sana⁵ ·
A. S. Al-Buloushi² · K. H. Hamed⁵

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Abstract Coastal erosion is observed in some locations along Al Batinah coast, Sultanate of Oman, and is an important factor to consider for the coastal zone management. The overall sediment supply by wadis to the coast is roughly 1.5×10^6 m³/year, out of which approximately 48 % is trapped by water retention dams. The remaining 52 % is more than eight times the sediment transport rate along the coast. The numbers indicate abundance of sediment supply with respect to removal rates but local conditions could vary. We investigated the potential erosion/accretion at selected sites including the SE and NW of major engineering structures such as harbors and desalination plants. Beach profile surveys were repeated five times for the study sites between February 2006 and March 2008 using a total station. The more detailed studies of the beach profiles broadly came to the conclusion that Al Batinah coast was fairly stable. The maximum erosion rate measured was 0.8 m/year. Most profiles showed some variability, but overall, there was stability over the monitoring period. The cases of accretion or erosion were all closely associated with harbors and other coastal engineering structures; however, no

cases were extreme. Seasonal accretion in the form of spring-tide berms of 1 m, sometimes varying from 1.5 to 2 m, was observed in June and November compared to the profiles measured in February. Most severe erosion and major sediment transport phenomena in Al Batinah coast are believed to occur during major storms events.

Keywords Beach erosion · Beach profiles · Al Batinah coast · Wadi sediment supply · Total station · Coastal zone management

Introduction

Sandy beaches, the focus of much human economic and recreational activities, dominate most temperate and tropical shorelines, including the coasts of the Sultanate of Oman. Despite their buffer role and resilience, sandy coasts in general and beaches in particular may not be stable in the long term. The stable shape of a sandy coastline at a certain location is the result of long-term equilibrium between natural and anthropogenic factors such as the rate of sediment supply by wadis, the rate of sediment removal by wave action and currents, and sand mining. This dynamic equilibrium is a critical part of natural coastal defense against storms; wave energy is neutralized in moving sand offshore and onshore. If the sediment supply is interrupted or reduced relative to the rate of removal, then the difference is compensated for by partial retreat of the coastline or coastal erosion. Accretion results from excess sediment supply relative to removal rates, causing the advance of the shoreline. Beaches are also usually characterized by longshore sand transport driven by oblique wave approach. Longshore transport is easily disrupted by coastal engineering structures.

✉ A. Y. Kwarteng
kwarteng@squ.edu.om

¹ Remote Sensing and GIS Center, Sultan Qaboos University, P.O. Box 33, Al-Khod, PC 123, Oman

² Department of Geography, Sultan Qaboos University, P.O. Box 42, Al Khod, PC 123, Oman

³ Illenberger & Associates, 55 Emerald Street, Mount Pleasant, Port Elizabeth, South Africa

⁴ Deanship of Postgraduate Studies, Sultan Qaboos University, Oman and The University of Sydney, Sydney, Australia

⁵ Department of Civil and Architectural Engineering, Sultan Qaboos University, P.O. Box 33, Al Khod, PC 123, Oman

The Omani coastline is up to 3000 km in length, depending on the method of measurement (JICA 2003). Most of this is soft shore subject to the dynamics of sediment transport. The sandy shoreline, or littoral active zone, is therefore a dynamic area including beaches, dunes, nearshore, and khawrs where sand is stored, transported, and exchanged. Sandy beaches are the central element of this sedimentary system and are considered buffer zones, protecting the coast from sea attack and erosion. Beaches may lose sand during storms and then recover it during calms, thereby maintaining equilibrium. Recognition of this important role of beaches and their place in Oman's history and culture is evidenced by the prominence given to them in the Sultanate's Coastal Zone Management Plan (IUCN 1986). Along Al Batinah coast, Sultanate of Oman (Fig. 1), erosion is observed in some locations and has been highlighted as an important factor to consider in coastal engineering activities (James Dobbin Associate Inc 1992; Atkins Consultants Ltd. 2001). Al Batinah beaches are mesotidal and tide-dominated with low wave energy and limited littoral drift of less than 100,000 m³/year (Hayes and Baird 1993). All beaches have reflective upper shores and broad tide-dominated terraces on their lower part. These vary in detail from place to place and are being continuously modified by the longshore transport and wave-driven movement of sand. The ability to regularly monitor the evolution of beach profiles in terms of space and time is essential for effective coastal management and scientific understanding of the ever changing coastal processes.

In this study, we investigated coastal erosion in Al Batinah by conducting repeated beach profile surveys SE and NW of major engineering structures. The surveys were part of a comprehensive coastal erosion project which included social economic studies, remote sensing assessment of coastal erosion, sediment type and provenance, and current and wave measurements in selected areas (Al Hatrushi et al. 2014). The project focused on the southeastern three-quarters part of Al Batinah coast where sediments derived from the Al Hajar Mountains range are carried to the coast by wadis (Fig. 1). These are then redistributed fairly uniformly along the coast by the action of waves, tides, and wind; so there is a reasonably consistent supply of sediment to the coast. Some of the questions to be addressed in this and other studies in the project include the following: (1) Is erosion still active? (2) What are the rates of erosion? (3) What is the net effect of major engineering structures on the rate of erosion and accretion? (4) What is the net contribution of water retention dams and other dams to the overall erosion and accretion processes?

Study area

Al Batinah coastal plain is located in the northeastern part of Oman and bounded between the Al Hajar Al Gharbi (Western

Hajar) Mountains and the Sea of Oman. It extends in a NW-SE trend as a crescent shape and parallel to the mountains for about 230 km from the United Arab Emirates (UAE) border in the NW to Muscat in the SE (Fig. 1). Al Batinah coastal plain is narrow at its northwestern and southeastern ends, while its greatest width in the middle is around 50 km. The coastal plain is composed of continuous alluvial fans drained from the mountains with sediment which varies from gravel and coarse sands to fine sands and silt near the coast. The coast alignment is fairly straight for a long distance and composed of sandy beaches and several tidal inlets and lagoons, with stands of mangroves near the drainage of major wadis. Because it is flat and fertile, the coastal zone is the most favorable place for human settlement and activities, including agriculture and fishing.

Al Batinah coast is one of the most fertile areas in Oman with the shoreline made up of more than 90 % of sandy beaches. Presently, the area is heavily settled with human settlement following the pattern of an almost continuous strip of towns and villages starting from As Seeb in the SE to Shinas in the NW. Al Batinah coastal plain has been experiencing rapid development over the past four decades. Residential and commercial housing, agricultural, and fishing activities have been concentrated along the coast. Infrastructure, including roads, corniches, markets, mosques, fishing harbors, and desalination plants, have been constructed along the coast. Some of the prominent engineering structures in 2004 included the Royal Navy of Oman (RNO) harbor at Widam, Sohar Port, Majis Jetty, Sohar industrial area water intake, Al Ghubrah and Barka desalination plant intake and brine disposal, and fishing harbors at Al Khaburah and Saham.

In general, Oman is classified as an arid region where precipitation is limited and variable. The average yearly rainfall recorded for all the Sultanate of Oman is 117 mm. However, the average rainfall in the Al Batinah plain is 101 mm per year (Kwarteng et al. 2009). Air temperature is high and varies from place to place, depending on location and altitude. The mean annual temperature for the whole of Oman is slightly below 30 °C. Evaporation rate is high and has been measured in Nizwa, in interior of Oman, as 1.29 m/year. Relative humidity is highest in the coastal areas almost throughout the year, especially during the summer months when it reaches a maximum of 99 %. In winter, the weather of Oman is influenced by the northwesterly and northeasterly winds, while in summer, it is influenced by the southwesterly monsoon. Air pressure, wind patterns, and precipitation are the main meteorological factors that are closely linked to the geomorphological processes on the coastline. These are the mechanisms responsible for coastal processes such as erosion, transportation, and deposition of sediments. Precipitation, on the other

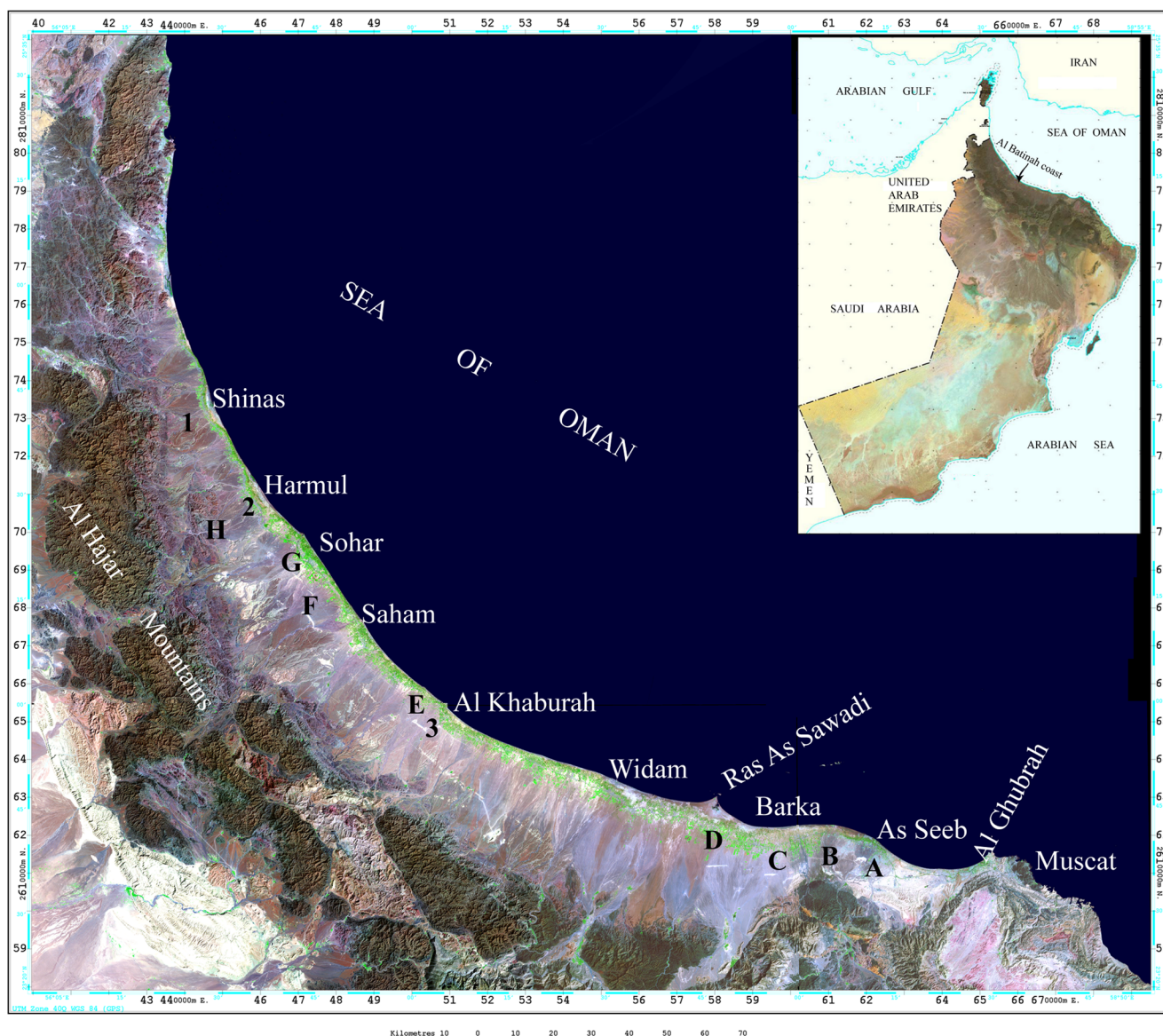


Fig. 1 The general location of the study area, Al Batinah coast, is shown in the inset image of Oman and surrounding countries. A detailed image of Al Batinah coast and study sites is shown in Landsat ETM+ bands 7, 4, and 2 color composite image acquired on October 28, 2000. The infrared band (TM band 4) was projected through a green filter, and therefore, significant vegetation appears in shades of green. The different colors

represent the diverse lithological units in the Al Hajar Mountains. *Letter annotations in black* refer to the following recharge dams: A=Al Khoud, B=Fulayj, C=Taww, D=Ma'awil, E=Hawasnah, F=Ahin, G=Hilti/Salahi, H=Al Jizi. *Numerical annotation in white* refers to location of the following: 1=Khawr Liwa, 2=Khawr Harmul, 3=Wadi Hawasnah

hand, causes the main wadis to flow to the sea, supplying sediment to the shoreline (Kwarteng et al. 2009).

Geological setting

The geology of Al Batinah coastal plain and coastal sediment is coupled to the geology of the North Oman Mountains which consists of tectonically emplaced late Paleozoic and Mesozoic continental margin and Tethys deep sea sediments along with a slab of Cretaceous oceanic crust and mantle, popularly known as Samail Ophiolites (Robertson 1990). North Oman

Mountains are lithologically composed of three consecutive main rock units in addition to Quaternary sediments (Hanna 1995). These main rock units from base to top are as follows:

- *The Autochthonous sequence:* These units are the oldest rocks exposed in the mountains and consist of the Precambrian crystalline basement of the Arabian platform as well as the pre-Permian shelf carbonates known as the Hajar Super Group sequence.
- *The Allochthonous sequence:* These rocks overlie the autochthonous sequence and are composed of the Hawasnah

Complex, Samail Ophiolites, and metamorphic rocks sandwiched between them.

- *The Late Tertiary and Quaternary deposits:* These include gravel terraces and fans in the alluvial plains, slope, and aeolian deposits. Along the coastline, surface deposits exhibit a mixture of terrestrial and marine deposits including coral terraces, raised beaches, aeolian sands, and alluvial gravel.

Recharge dams

Wadis are the main source of sediment supply to Al Batinah coastal region. In the event of heavy rains, especially in coastal areas, surface runoff in the wadis lasts for a few hours to a few days due to high topographical slope, very coarse topsoil, and their absolutely dry conditions. The Ministry of Water Resources has constructed several recharge and water retention dams to retain some of the water during storms for effective recharging of the groundwater (Ministry of Water Resources 1998; see Fig. 1). Because rainfall events are intermittent in space and time, so is sediment supply, which may cause natural short-term reversible erosion/accretion cycles. The general outline of drainage basins and location of rain gauges in Al Batinah and Muscat region is presented in Fig. 2.

Oceanographic factors

Two seasonal prevailing winds, the NE winter monsoon and the SW summer monsoon, dominate the climate in the coastal areas of Oman. Consequently, sea waves along the coastline of Oman are affected by these two wind systems. However, there is a distinct difference between wave energy in the Sea of Oman and that in the Arabian Sea (Wimpol Ltd. 1986). Over the Sea of Oman, where fetch is limited and the winds are generally light to moderate, waves are generally small with heights less than 1 m. Rough seas with waves of greater than 1.5 m in height occur only during storm events in winter. In the Arabian Sea, where fetch is greater and winds are stronger, waves are more energetic, with maximum heights of 3 m in winter and 6–7 m at the peak of the summer monsoon.

The general current circulations are closely linked to the wind systems (Wimpol Ltd. 1986). However, there is a distinct difference between the circulation in the Sea of Oman, where the prevailing winds are gentle, and the Arabian Sea where the prevailing winds are relatively strong. In the Sea of Oman, the current circulations are influenced by the prevailing north and NW winds, the large-scale eddies in the eastern Sea of Oman, and the outflow from the Arabian Gulf. The general current circulations are weak and have a tendency to flow around the coast of the Sea of Oman in an anticlockwise direction. The tidal regime of the Oman coastline is semidiurnal, characterized by two high waters and two low waters per day with a large diurnal

inequality in high and low water levels. The tides have a daily range on average of 1.5–2 m, with a maximum range in the order of 3 m. The predicted astronomical tide ranges from a lowest of 2 m in the south to a highest of 3.5 m in the north (National Hydrographic Office 2014).

Apart from the latitudinal temperature gradient, the sea surface temperature along the coastline of Oman is controlled by the strong upwelling associated with the summer monsoon. Sea surface temperature between December and March shows an increase from north (23 °C in the Strait of Hormuz) to south (25 °C in the Arabian Sea). However, in May, sea surface temperature rises to 28–29 °C along the entire coast of Oman. In August, during the peak of the SW monsoon, temperatures fall to 22–23 °C along the SE coast of Oman in the Arabian Sea because of the intense upwelling, while in the Sea of Oman, temperature rises to 32 °C.

Longshore drift is low along Al Batinah coast. Northwest of Widam, longshore drift is northwestward and SE of Widam longshore drift is southeastward (Hayes and Baird 1993). This may be in response to (1) large water circulation gyres in the Arabian Sea and Sea of Oman, (2) changes in wave patterns along Al Batinah coast, and (3) variations in the amount of sediment brought to the coast by wadis; longshore drift will move sediment away from areas where more sediment is supplied by wadis.

Sea level rise

Sea level rise associated with climate change is also a factor impinging on sandy coasts worldwide. Absolute sea level has been well below the present height for most of the last 120 thousand years, until the sea level returned to the present day values about ten thousand years ago. Sea level rose above the present height by a few meters at most, 6000 years ago (Lambeck et al. 2002). In Oman, coastal geomorphological evidence suggests that sea level was about 1.5 to 2 m above the current level about 6000 years ago followed by regression to the present day. The land mass of Oman is continuously being uplifted at a rate which is faster than the projected sea level rise. Consequently, sea level rise does not appear to be a major contributor to coastal erosion in Oman.

Tropical cyclones

Tropical cyclones occur infrequently along the Sea of Oman and more so in the Arabian Sea. During the study period, the southeastern part of Oman including south Al Batinah coast was affected by cyclone Gonu, which was the strongest tropical cyclone to hit the Arabian Peninsula on June 4, 2007 (Kwarteng 2010). The cyclone brought along strong and torrential rains, high waves, and strong winds. Gonu was first observed as incipient tropical depression in the Indian Ocean on May 27 by weather satellites. Gonu peaked to category 5

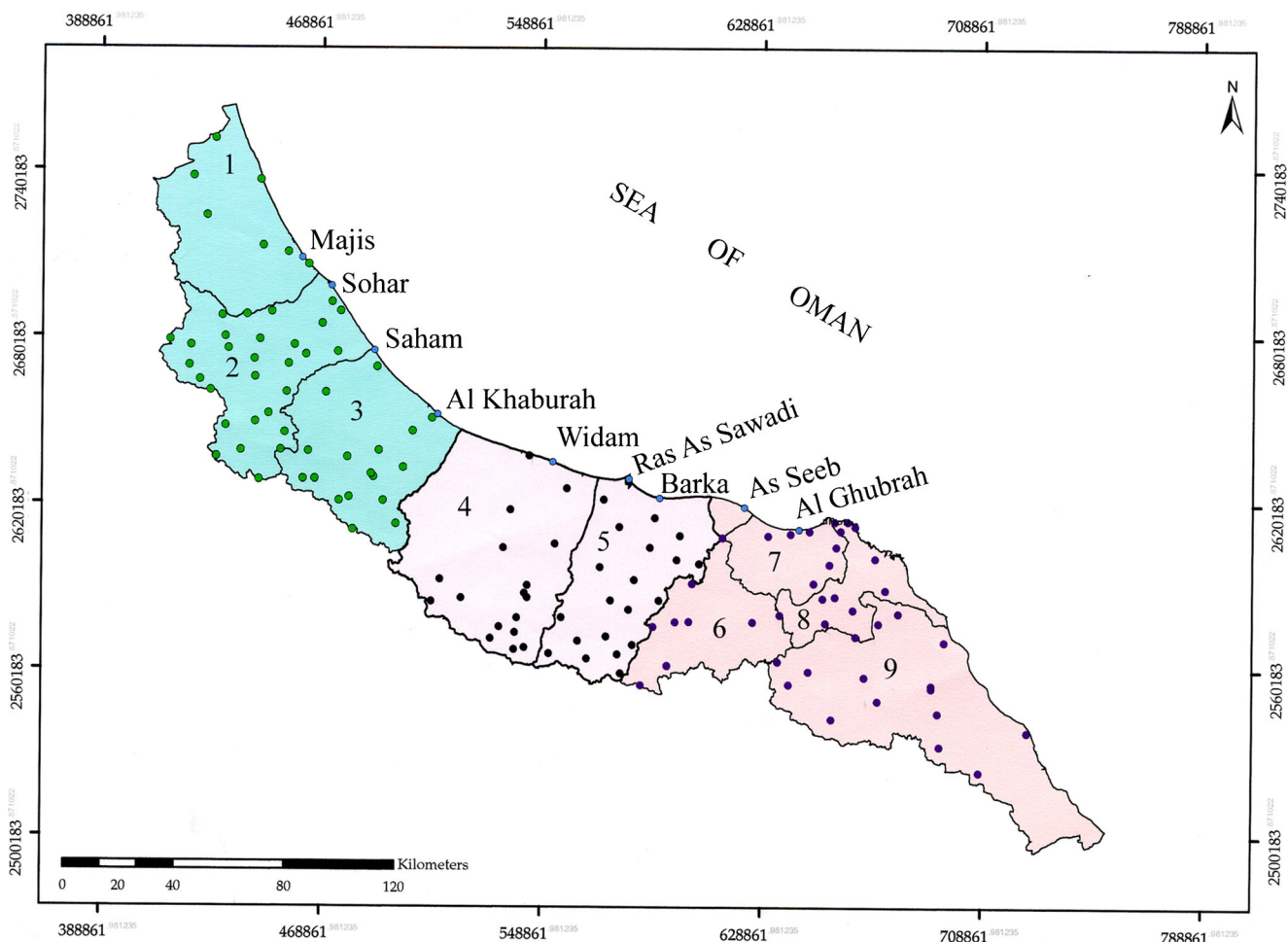


Fig. 2 Outline of drainage basins (area of approximately 12,000 km²) that influence sediment transport to Al Batinah coast and Sea of Oman. The circular dots show the locations of rain gauges. Annotation refers to

the following drainage basins: 1=Shinas, 2=Sohar, 3=Saham, 4=Ar Rustag, 5=Barka, 6=Samail, 7=Al Khuwayr, 8=Muscat, 9=Qurayyat and Tiwi

(wind speed ≥ 252 km/h) on June 6 but was downgraded to category 1 (wind speed between 119–153 km/h) by June 8, 2007. As the storm weakened, it moved through the Arabian Sea and made a landfall in Iran on at 0.00 GMT on June 7, 2007. The most seriously affected areas in Oman included Sur, Qurayyat, and parts of Muscat Governorate. In the city of Muscat, the torrential rains from Gonu turned wadis and roads to apparent rivers, and low areas to lakes at the scale never recorded in the history of the Sultanate of Oman. Unfortunately, the effect of cyclone Gonu could not be monitored in this study. The areas NW of Barka were not affected. Monuments used as benchmarks in areas where Gonu occurred were destroyed.

Materials and methods

From reconnaissance field surveys conducted in September 2004, nine sites were selected for further studies, including beach profiles surveys and sediment analysis. The areas close

to major engineering structures, such as harbors and desalination plants, were identified as being priority sites for monitoring coastal erosion and accretion. The sites are described from NW to SE including some field observations in 2004 (see Fig. 1).

Site 1—Harmul, Sohar Port, and Majis The whole area was undergoing tremendous changes caused by construction of the new Sohar Port (Atkins Consultants Ltd. 2002). Between 2004 and 2007, the benchmarks and study areas close to the harbor and its environs were lost to expansion of the Sohar Port. Continuous beach monitoring was limited to only parts of Harmul. Prior to construction, it was observed that the areas west of the Sohar Port, including Harmul (Khawr Harmul) and Khawr Liwa, were experiencing slight erosion, indicating that the sediment transport was from SE to NW. In addition, the area around Majis Jetty was severely eroded.

Site 2—Hilat Al Sauk, Sohar A new fishing harbor was under construction, and the area to the west of the harbor

might experience severe erosion in the future as sediment transport seems to be from SE to NW. Southeast of the harbor, the corniche was protected by a sea wall. Further SE, there was erosion along most of the beach, starting from Hilat Al Shizaw to Hilat Al Shaikh. The area was selected to monitor sediment movement to the SE and NW of a new harbor under construction in 2004. However, surveys were limited to the NW of the harbor because of the sea wall to the SE.

Site 3—Saham The coastline SE and northwestward from Khawr Al Hamam fishing harbor (constructed in 2002) was stable and not severely affected by erosion or accretion. However, Harat Al Za'ab and Harat Al Ajam, where a major sea wall was under construction, were affected by coastal erosion, suggesting SE to NW sediment transport as well as a beach deprived of sediments (Fig. 3b).

Site 4—Al Khaburah There is an offshore breakwater forming a harbor linked to the beach by a pier. To the eastern side of Al Khaburah, the beach was reasonably stable up to the fishing harbor (designed to allow sediment transport). However, the western side of the harbor was experiencing severe erosion for about 6 km (Fig. 3a). That might suggest sediment transport from SE to NW. The beach may be deprived of the sediment brought to the coast via Wadi Al Hawasnah, which does not reach the coastline anymore because of the recharge dam built inland.

Site 5—Widam The site inside the headquarters of the Royal Navy of Oman (RNO) was approaching stability according to the

Fig. 4 Profile surveys with spacing of 300–800 m were run from the shore and perpendicular to the shoreline to reach the low water mark. The figure shows the layout of the surveying lines at Harmul (HR1–HR6) and Majis (MJ1–MJ6) superimposed on 2004 Ikonos satellite image. The red circles denote the locations of the monuments for each profile. The light areas at Sohar Harbor indicate the onset of construction of the new harbor

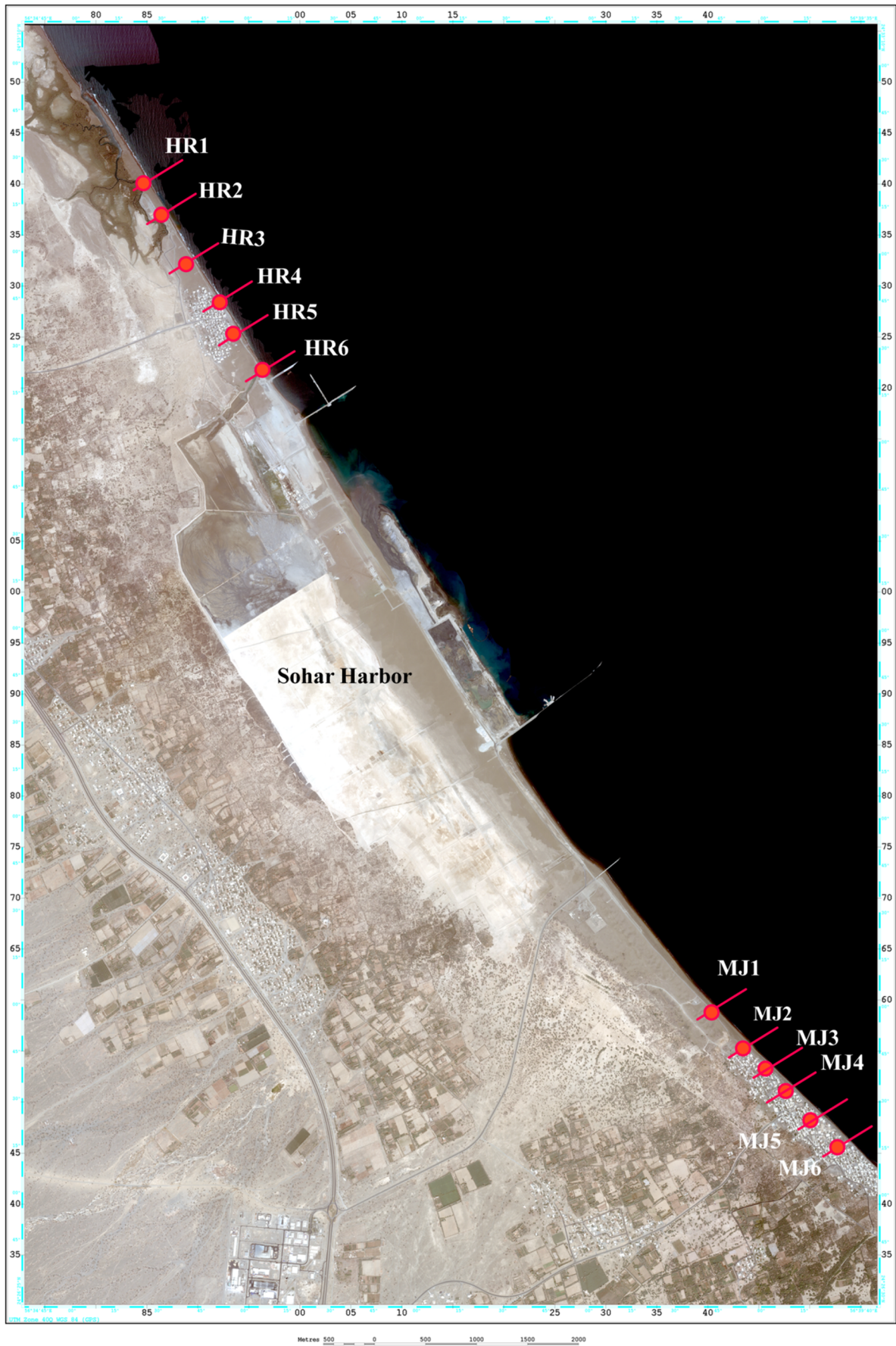
surveying RNO. However, the SE side of the harbor was critically eroded. The NW side was experiencing accretion, especially the pocket beach between the groyne and the western breakwater, in which sediment was trapped. Clearly, this shoreline was also experiencing sediment transport from NW to SE. Groynes and wadi input adds complexity to the picture. The shore was eroding at Widam Sahil to the SE (Fig. 3c).

Site 6—Ras As Sawadi This is a salient point, developed over the last few thousand years since sea level stabilized, and resulting from the shelter caused by the closest Damaniyyat Islands. There was accretion in the western side of the salient and some localized erosion on the southeastern side parallel to the tarred road. However, the sand spit in the adjacent khawr was growing westward, suggesting another system of sediment transport from SE to NW in this segment of the coastline. Overall, this was an area of significant shoreline growth and sand accumulation in the long term. Further beach monitoring in the area was not possible due the commencement of the construction of Blue City (Al Madinah Az Zarqa) development.

Site 7—Barka Desalination Plant There were signs that this area was experiencing slight erosion but there were no significant problems. This desalination plant is smaller in structure

Fig. 3 Field photos showing erosion along Al Batinah coast in September 2004. **a** Erosion at Al Khaburah; **b** erosion and dumping of pieces of rock to slow down the wave action at Saham; **c** severe erosion at Widam village, east of Royal Navy of Oman headquarters. Construction debris has been dumped to slow down the erosion; **d** critical erosion of about 2–3 m high east of Al Ghubrah desalination plant. Blocks of construction debris have been dumped to protect the plant from further erosion





but with higher capacity than the one at Al Ghubrah. No breakwaters or jetties are present as the discharge and intake pipes are buried underground. The plant was constructed approximately 200 m from the shore in an area which was not heavily populated, so there was no significant impact on the beach. The location was selected to represent a stable area with insignificant erosion.

Site 8—As Seeb Whereas the area between Al Ghubrah and As Seeb was stable and protected by fields of sand dunes, As Seeb coastline was experiencing a slow process of erosion. However, the corniche is protected by a substantial sea wall. There were areas where the beach was stable and sand dunes were protected by vegetation. In some areas, where wadis met the sea, the coastline had extended slightly due to sediment discharge.

Site 9—Al Ghubrah Desalination Plant To the west side of the desalination plant jetties, there was accretion (although bedrock was exposed) where fishing boats were landed. The accretion had been cut by the new extension of the plant (where the water was discharged) and a small pocket sand beach had developed between the discharge area and the breakwater (a sediment trap). The SE side of the desalination plant was experiencing critical erosion for about 1 km and bedrock was exposed in the inter-tidal zone. The erosion line was about 2–3 m high. Blocks of construction debris had been dumped to protect the plant from wave action (Fig. 3d). Sediment was also trapped between the jetties. Sediment transport in this segment of the coastline was from NW to SE. Therefore, there was accretion on the NW side and critical erosion on the SE side.

Beach profiles data were acquired every 4 months during spring low tide in February 2006, June 2006, November 2006, February 2007, and February–March 2008, using a Sokkia Total Station Set 3030R, an electronic instrument for measuring points in three-dimensional space. Initially, 84 profiles consisting of approximately four to six lines each on the SE and NW side of the major coastal engineering structures in Al Batinah coast were selected for field surveys. Monuments, which were used as benchmark on each profile, were designed and cast with concrete; 84 of these, each weighing more than 80 kg, were partially buried, exposing only the top part at the study sites along Al Batinah coast during 2005 and early 2006. Each monument was tagged with a numbered brass plate. However, several of the monuments were later lost due to the combination of urban expansion, coastal development projects, sand encroachment, and the effects of cyclone Gonu, which struck the southeastern coast of Oman on June 4, 2007. Each profile survey was run from the shore and perpendicular to the shoreline to reach the low water mark. The spacing between the profiles at the different sites was between

300 and 800 m. Figures 4 and 5 show the profile layout at Sohar Harbor and Al Khaburah. During the surveying, the same azimuth/bearing was repeated for each beach profile from the benchmarks.

Due to equipment limitations, the coordinates of the monuments were initially surveyed using a handheld Trimble GeoExplorer 3 Global Positioning System (GPS). In May 2008, the remaining monuments were surveyed to high accuracy of approximately 2 cm in vertical and horizontal directions using Real Time Kinematics (RTK) GPS survey equipment (Table 1). All the data were re-calculated to reflect the RTK GPS measurements. During the GPS RTK and static survey, one receiver was a base station on a control point with network adjusted or published coordinates. The second receiver was used as a rover to measure the coordinates of an unknown point. The raw GPS data collected from the base station receiver was transmitted through a radio modem to the rover providing real-time corrections based on the resolved ambiguities of the satellite constellation at the time of the survey. Consequently, the rover unit could provide accurate absolute positioning values that can be viewed in real-time along with other quality indicators. The rover unit recorded points automatically when they fell within a user-defined accuracy and survey criteria. The data were observed and reduced in the field and processed subsequently. The National Survey Authority of Oman (NSA) established controlled points, and the World Geodetic System 1984 (WGS84) datum and spheroid referencing system were used in this project.

Beach profile plots with emphasis on vertical accretion/erosion were generated using Microsoft Office Excel program. Wadi sediment supply at the Al Batinah coast was calculated from sediment measurement and removal records provided by the Ministry of Regional Municipality and Water Resources (MRMEWR).

Results

Wadi sediment supply

The dams control the runoff from an area of around 5750 km² out of the roughly 12,000 km² total drainage area of Al Batinah drained toward the Sea of Oman. From Table 2, the overall average sediment supply rate is approximately 80 m³/km²/year. Using this rate, 960,000 m³/year sediment is supplied from all Al Batinah coastal plain area, out of which some 460,000 m³/year is currently trapped by the recharge dams.

The actual sediments removed from other dams by the Ministry of Regional Municipalities, Environment, and Water Resources (MRMEWR) as part of their maintenance plan is presented in Table 3. Analysis of these data, after calculating the average per year sediment accumulation and adjusting for the average flow in the sedimentation period relative to the long-term average flow calculated from the

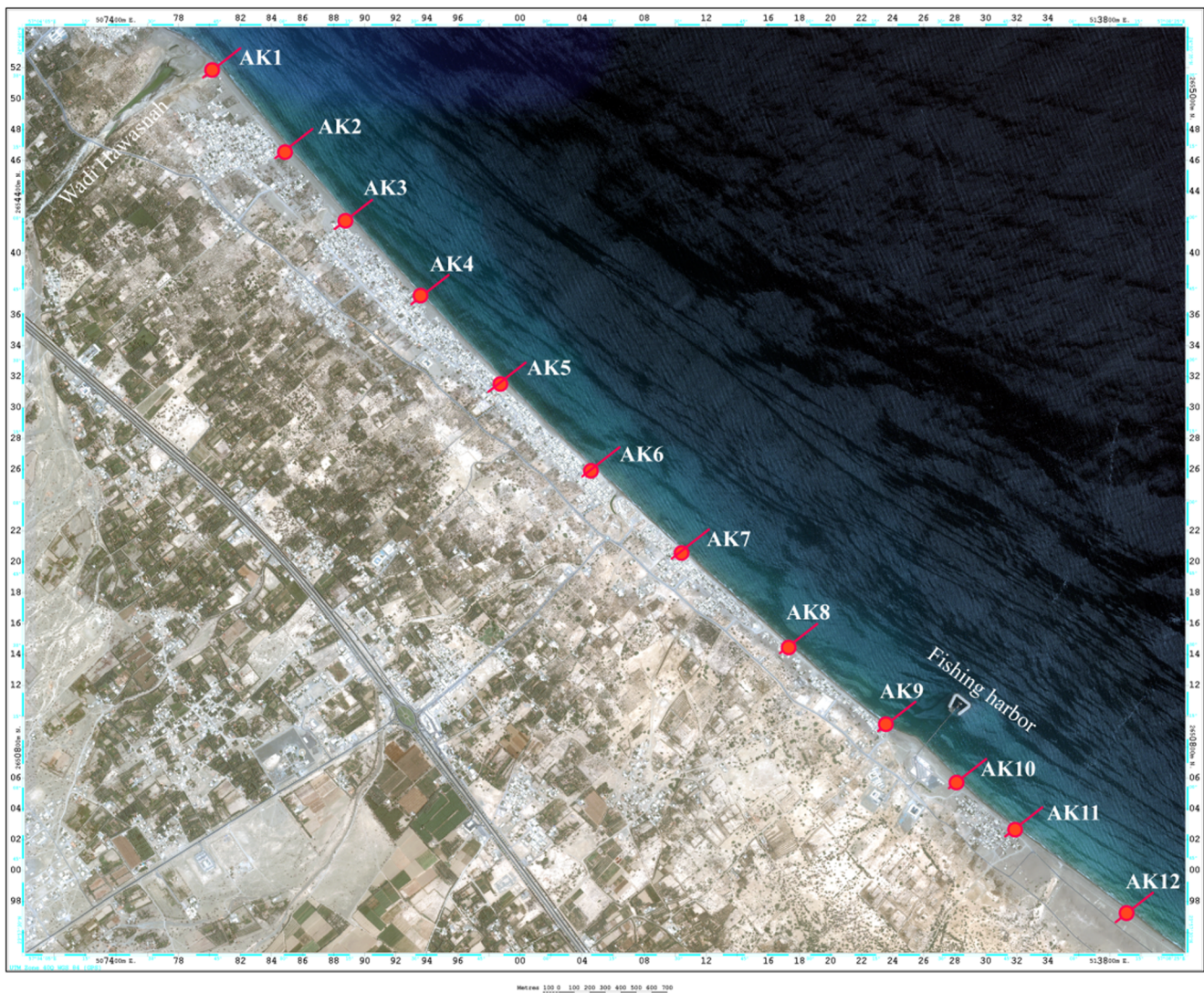


Fig. 5 Profile surveys with spacing of 300–800 m were run from the shore and perpendicular to the shoreline to reach the low water mark. In this image, the survey profile layout at Al Khaburah superimposed on an

Ikonos image. Wadi Al Hawasnah is shown in the NW part of the image. The *red circles* denote the locations of monuments for the profiles

data, indicates an average sedimentation rate of some 130 m³/km²/year. This number is higher than the average for the whole Oman (80 m³/km²/year as given above) but is very close to the average of 129 m³/km²/year from Al-Jizzi and Hilti-Salahi dams (Table 2). Based on this more relevant rate, the sediment supply from all Al Batinah coastal plain area amounts to roughly 1,560,000 m³/year, out of which some 747,500 m³/year is currently trapped by recharge dams. This means that roughly 48 % of the natural sediment supply is currently trapped by recharge dams in Al Batinah coastal region.

Beach profiles

Beach profiles are presented in order from NW to SE along Al Batinah coast. Not all the datasets are complete: There are 31

full datasets, 26 datasets that cover 1 year, and 7 datasets that were only measured in February 2006 and June 2006. Inter-annual changes were obtained by plotting only the surveys done in February 2006, February 2007, and February/March 2008. Graphs of seasonal changes were plotted from surveys in February 2006, June 2006, November 2006, and February 2007. Table 4 is a summary of the major inter-annual erosion/accretion along profiles with complete datasets described below.

Inter-annual changes

Harmul: Twelve profiles, six north and six south of the Sohar Port, were selected for further monitoring. The benchmarks and study areas close to the harbor were lost to expansion of the Sohar Port. Only two of the sites north of

Table 1 Average sediment measurement at selected dams (MRMEWR 2003)

Dam	Sediment rate (m ³ /km ² /year)
Al Jizzi	99
Hilti/Salahi	159
Quryyat	19
Tanuf	119
Ghul	84
Al Aflaj (Sur)	36
Kabir (Araqi)	36
Average	78.86

Sohar Port (lines HR1 and HR2) have complete datasets for the study period. The profiles show yearly erosion of up to 0.7 m/year (Fig. 6). Accretion of up to 0.4 m/year was observed on the upper beach of line HR1 in 2006–2007.

Hilat Al Sauk, Sohar: Out of the five survey lines west of the fishing harbor, lines HSW4, HSW2, and HSW1 had complete measurements. The site experienced erosion with a maximum rate of 0.6 m. Erosion rates were higher in 2007–2008 than in 2006–2007. Erosion was observed at lines HSW4 and HSW2 (Fig. 7). However, at line HSW1 (closest to the fishing harbor), accretion of up to 0.3 m/year was observed.

Saham: Ten surveying lines were selected to monitor sand movement SE and NW of a recently constructed fishing harbor. Four of the sites had complete measurements and five had data from June 2006 to June 2007. Accretion was observed in the upper beach mainly from 2007 to 2008, while accretion occurred in the lower beach SE of the new fishing harbor at Saham (Fig. 8). Steepening of the beach due to lower wave energy in the lee of new harbor occurred. The abnormal behavior is attributed to the construction of the new dam.

Al Khaburah: Twelve survey lines were selected SE of Wadi Al Hawasnah including the fishing harbor. Six of the lines had complete measurements, five had partial

Table 2 Sediment removal at selected dams in Al Batinah region between 1998 and 2004 (MRMEWR 2004)

Dam	Location	Year	Volume (m ³)
Al Hawasnah	Al Batinah north	1998	783,000
A'hin	Al Batinah north	1998	952,000
Hilti-Salahi	Al Batinah north	2000	639,000
Al Fara'	Al Batinah south	1998	65,000
Al Fara'	Al Batinah south	2000	65,000
Al Fara'	Al Batinah south	2004	63,000

measurements, and one was destroyed. Erosion took place at line AK1 located at the mouth of Wadi Hawasnah. Presumably, the delta formed by sediments deposited by the wadi was being slowly eroded. The wadi has been dammed since 1995, resulting in very limited sediment reaching the coast (Kwarteng 2008). The other sites were variable but, overall, little changes were observed. An accretion of up to 1 m/year was observed at the middle beach at line AK10 (Fig. 9). A fishing harbor (constructed in 2001) in the form of an offshore jetty has been built near to line AK9. This seems to have had less effect on longshore drift than conventional harbors.

Widam: Eight out of the ten profiles had complete measurements. Overall, little change was observed on the western part of the harbor at lines WDW5, WDW4, and WDW3. Construction of the harbor walls started in 1983 and was completed in 1985. On the SE side of the harbor at lines WDE7, WDE6, and WDE5, no overall changes were observed. Accretion took place at line WDE4 from 2006 to 2008. The profile position was at the edge of Widam village. The “accretion” was probably due to human activities in the area—depositing material on the upper profile. At line WDE1 (Fig. 10) accretion occurred on the upper profile from 2007 to 2008.

Barka: The site was selected to monitor any potential changes near the Barka desalination plant. The site has three complete measurements and three measurements from 2006 to 2007 and two were destroyed after cyclone Gonu. No significant changes were observed at lines BRW3 and BRW2 from 2006 to 2007. However, accretion of up to 1.5 m/year took place from 2007 to 2008 (Table 4). This was most likely due to sediment input from a wadi that carried sediment to the coast during the floods resulting from cyclone Gonu. Line BRW0, directly in front of the desalination plant, showed accretion at the upper slope and erosion at the lower slopes between 2007 and 2008. Little overall change was observed.

As Seeb: Six profiles were selected along the coast of As Seeb. A substantial seawall was constructed starting in 2005 to protect the corniche. Most of the study sites were lost due to the construction and the impact from cyclone Gonu. The seawall toe was 20 m from the monument of line SB2 with the only complete dataset. The remaining beach from 20 m seaward of line SB2 showed little change.

Al Ghubrah: Six lines, three each on the SE and NW of the Al Ghubrah desalination plant, were selected for further studies. Four lines had complete measurements while two were lost. Between 2007 and 2008, some accretion was observed at lines AGW1 (Fig. 11), AGE1, and AGE2. Line AGE5 was stable with minor changes.

Table 3 Hand held GPS and GPS RTK coordinates of monuments

	Location	Monument ID	Brass plate no.	Handheld GPS coordinates			GPS RTK coordinates		
				Northings	Eastings	Elevation (m)	Northings	Eastings	Elevation (m) (msl)
1	Harmul	HR1	47	2714074.26	458461.72	1.83	2714072.438	458460.467	4.360
2	Harmul	HR2	16	2713737.94	458649.88	2.95	2713737.786	458648.893	5.581
3	Sohar Sauk	HS-W4	64	2697769.35	472447.89	1.01	2697771.071	472459.974	3.450
4	Sohar Sauk	HS-W2	76	2696936.65	472945.06	2.78	2696983.260	472927.831	3.985
5	Sohar Sauk	HS-W1	23	2696444.32	473242.82	1.18	2696446.329	473255.281	4.213
6	Saham	SM-E1	80	2670893.68	490539.67	3.24	2670880.384	490555.441	3.532
7	Saham	SM-E2	58	2670454.97	490890.06	3.67	2670458.023	490883.919	3.349
8	Saham	SM-E3	11	2670134.55	491111.07	1.89	2670130.251	491117.788	3.329
9	Saham	SM-E4	19	2669676.96	491450.99	1.51	2669704.693	491439.770	3.904
10	Saham	SM-E5	50	2669227.86	491805.61	2.55	2669239.900	491826.900	4.465
11	Al Khaburah	AK-1	22	2655183.54	508036.22	1.23	2655193.633	508027.275	2.818
12	Al Khaburah	AK-2	43	2654676.28	508443.58	2.33	2654636.790	508483.860	3.485
13	Al Khaburah	AK-7	28	2652004.2	511096.24	7.03	2652022.917	511078.927	4.256
14	Al Khaburah	AK-8	18	2651446.75	511697.62	7.96	2651453.427	511706.239	5.014
15	Al Khaburah	AK-9	33	2650913.54	512322.79	2.69	2650919.874	512334.256	3.391
16	Al Khaburah	AK-10	75	2650578.76	512789.81	7.52	2650569.970	512789.697	4.444
17	Widam	WDM-W6	10	2635947.54	550506.01	4.25	2635942.441	550505.411	2.392
18	Widam	WDM-W5	56	2635749.89	550948.06	3.65	2635745.790	550948.757	2.713
19	Widam	WDM-W4	14	2635620.55	551283.84	10.07	2635616.694	551282.561	2.577
20	Widam	WDM-W3	74	2635445.11	551688.47	0.5	2635439.445	551687.864	2.351
21	Widam	WDM-W2	8	2635307.65	552114.58	1.01	2635301.204	552113.862	2.265
22	Widam	WDM-E1	67	2632645.74	558228.16	2.21	2632644.335	558227.258	1.518
23	Widam	WDM-E2	36	2632891.03	557669.08	1.42	2632890.260	557667.456	1.864
24	Widam	WDM-E4	78	2633157.27	557033.4	0.5	2633154.723	557032.419	1.48
25	Widam	WDM-E5	24	2633378.29	556521.26	7.52	2633375.914	556519.012	2.436
26	Widam	WDM-E6	34	2633518.71	556127.99	7.79	2633514.827	556124.622	3.704
27	Widam	WDM-E7	55	2633671.18	555775.54	6.47	2633668.308	555774.429	3.444
28	Barka	BR-W3	73	2622308.92	598527.47	7.92	2622305.827	598527.730	2.406
29	Barka	BR-W2	79	2622320.43	598569.73	7.76	2622370.041	599130.682	2.703
30	Barka	BR-W1	70	2622404.45	599436.97	7.92	Not available		
31	Barka	BR-W0	40	2622544.85	600331.42	12.9	2622543.733	600329.120	2.285
32	As Seeb	SB-2	38	2618607.98	622946.72	9.56	2618634.596	622906.795	3.121
33	As Seeb	SB-3	27	2617571.31	624013.88	13.81	2617592.869	623987.504	3.751
34	Al Ghubrah	AG-W1	62	2611070.94	643725.1	8.75	2611069.421	643721.818	3.879
35	Al Ghubrah	AG-E1	30	2611216.04	644490.41	8.28	2611214.678	644491.940	4.104
36	Al Ghubrah	AG-E2	1	2611227.9	644614.05	12.11	2611227.686	644596.595	3.934
37	Al Ghubrah	AG-E5	54	2611312.75	645680.35	7.62	2611307.870	645471.723	2.822

Seasonal changes

In most cases, beaches were accreted in June 2006 and November 2006 compared to the profiles measured in February 2006 and February 2007. The accretion was generally in the form of a spring-tide berm at 1 m/year, sometimes varying from 1.5 to 2 m/year (Figs. 6–11).

Discussion

Coastal erosion occurs in Al Batinah, in part, as a natural process of continuing change of the shoreline. Hayes and Baird (1993) presented a brief physical setting and geomorphology of the Oman coast, emphasizing the areas with the most dramatic erosional/depositional cycles. They indicated that sediments on the beach in Al Batinah are derived from six main sources

Table 4 Maximum erosion/accretion along survey profiles east (E) and west (W) of major engineering structures on Al Batinah coast

Location	Monument ID	Maximum erosion/accretion (m)—2006–2007	Maximum erosion/accretion (m)—2007–2008
Harmul	HR1	0.4-m accretion on upper beach; stable at lower beach	0.5-m erosion
Harmul	HR2	0.7-m erosion	0.7-m erosion
Sohar Sauk	HSW4	Little change	0.4-m erosion
Sohar Sauk	HSW2	0.3-m erosion at mid beach; Little change at upper and lower beach	0.6-m erosion at mid beach; little change at upper and lower beach
Sohar Sauk	HSW1	Little change	Little change at upper beach; 0.3-m accretion at lower beach
Saham	SME1	Little change	Little change
Saham	SME2	Little change at upper and lower beach; 0.3-m erosion at middle beach	1-m accretion at upper beach; 0.4-m erosion at lower beach
Saham	SME3	Little change	0.7-m accretion at middle beach; 0.4-m erosion at lower beach
Saham	SME4	Little change	0.7-m accretion at middle beach; 0.4-m erosion at lower beach
Al Khaburah	AK1	0.8-m erosion at middle beach	Little change at upper beach; 0.6-m erosion at lower beach
Al Khaburah	AK2	Little change	Stable upper beach; 0.7-m accretion at lower beach
Al Khaburah	AK7	Little change	Little change at upper beach; 0.4-m erosion at lower beach
Al Khaburah	AK8	Little change	0.4-m accretion at upper beach; 0.5-m erosion at lower beach
Al Khaburah	AK9	Stable upper beach; 0.4-m erosion at lower beach	0.5-m erosion at middle beach; stable at lower beach
Al Khaburah	AK10	Little change	1-m accretion at middle beach; 0.4-m erosion at lower beach
Widam	WDW5	Little change	Little change at upper beach; 0.5-m erosion at lower beach
Widam	WDW4	Little change	Little change at upper beach; 0.7-m erosion at lower beach
Widam	WDW3	0.6-m erosion at middle beach; 0.4-m accretion at lower beach	0.9-m accretion at middle beach; 0.6-m erosion at lower beach
Widam	WDE7	Little change	Little change at upper beach; 0.6-m erosion at lower beach
Widam	WDE6	0.7-m erosion at lower beach	Little change
Widam	WDE5	Little change	0.6-m accretion at lower beach
Widam	WDE4	0.5-m accretion at mid beach	1.9-m accretion at lower beach
Widam	WDE1	Stable at upper beach; 0.8-m erosion at lower beach	1-m accretion at upper beach
Barka	BRW3	Little change	1-m accretion
Barka	BRW2	Little change	1.5-m accretion
Barka	BRW0	Little change	0.5-m accretion at upper beach; 0.5-m erosion at lower beach
As Seeb	SB2	Little change	Little change
Al Ghubrah	AGW1	Little change at upper beach; 0.4-m accretion at lower beach	Little change at upper beach; 0.3-m accretion
Al Ghubrah	AGE1	0.5-m accretion at upper beach; 0.5-m erosion at lower beach	0.5-m accretion at upper beach; 0.7-m accretion at lower beach
Al Ghubrah	AG2	Little change	0.5-m accretion at upper beach; 0.6-m accretion at lower beach
Al Ghubrah	AG5	Little change	Little change

Little change or stable refers to erosion/accretion less than 0.2 m

including drainage basins, eroding headlands, offshore carbonates, pelagic and bottom-dwelling organisms, onshore sand

dunes, and remote alongshore areas. However, sediments supplied by wadis are the most applicable source.

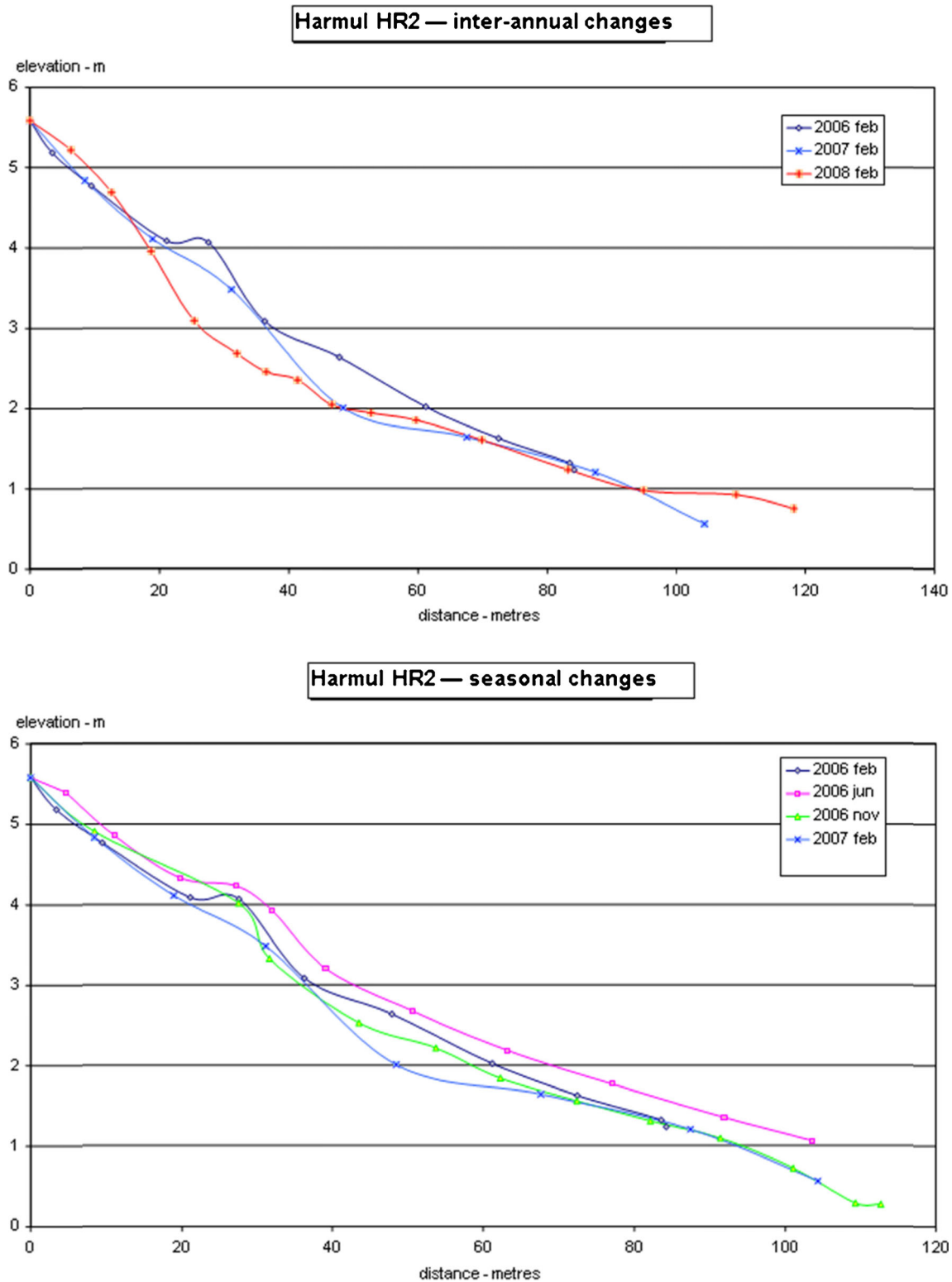


Fig. 6 Survey plots showing inter-annual and seasonal changes at line HR2 (Harmul) located on the NW part of the new Sohar Port. Erosion took place at this site as shown above. There was more accretion in June 2006 compared to the other survey months (below)

Field visits during this study and other studies indicate widespread erosion in parts of Al Batinah coast (see Fig. 4). Hayes and Baird (1993) suggested that during periods of

lowered sea level, a series of cone-shaped wadi fans formed along Al Batinah coast. When sea level reached the present relative stillstand, the shoreline was irregular with

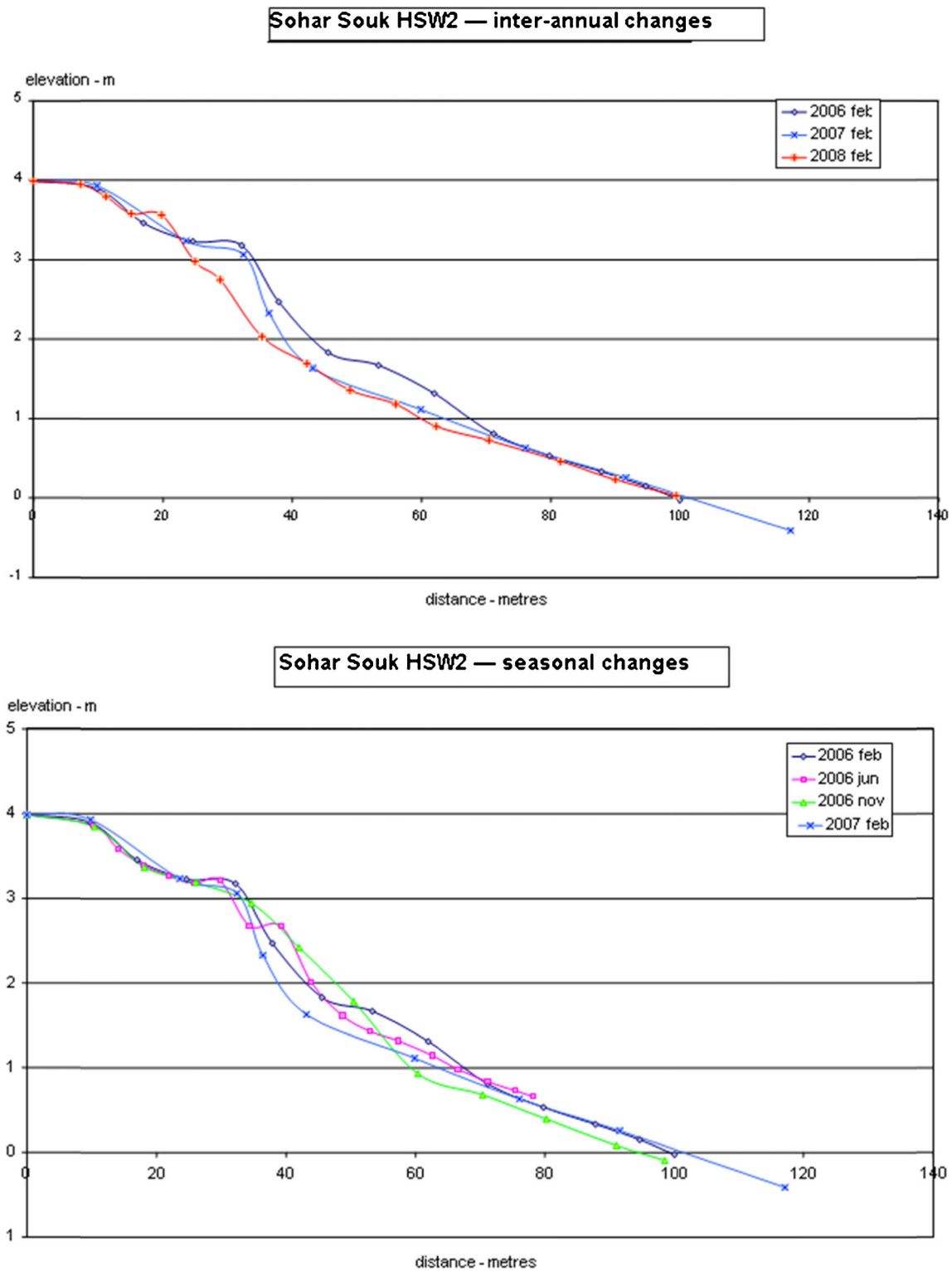


Fig. 7 Inter-annual and seasonal changes at lines HSW2 (Sohar Souk) located on the NW of the new Sohar fishing harbor. Erosion took place at these sites. The seasonal plot shows some erosion in the middle part of the profile compared to the other seasons

embayments occurring between the headlands. Since the beginning of this relative stillstand, the shoreline has undergone a straightening process, whereby the headlands were eroded and the embayments were filled in. As a result of this process,

erosional and depositional areas are interspersed all along the shoreline. James Dobbin Associate Inc (1992) attributed the severe and irreversible erosion observed in parts of Al Batinah coast to construction of dams, harbors, roads, and other

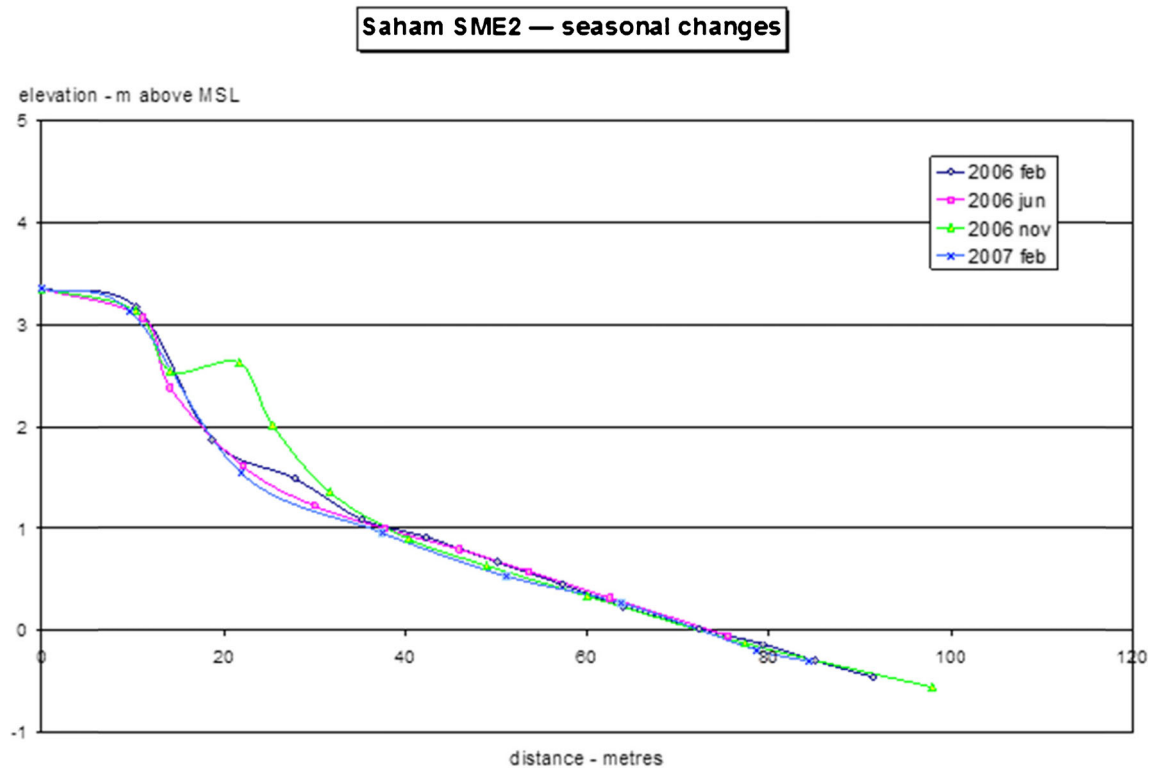
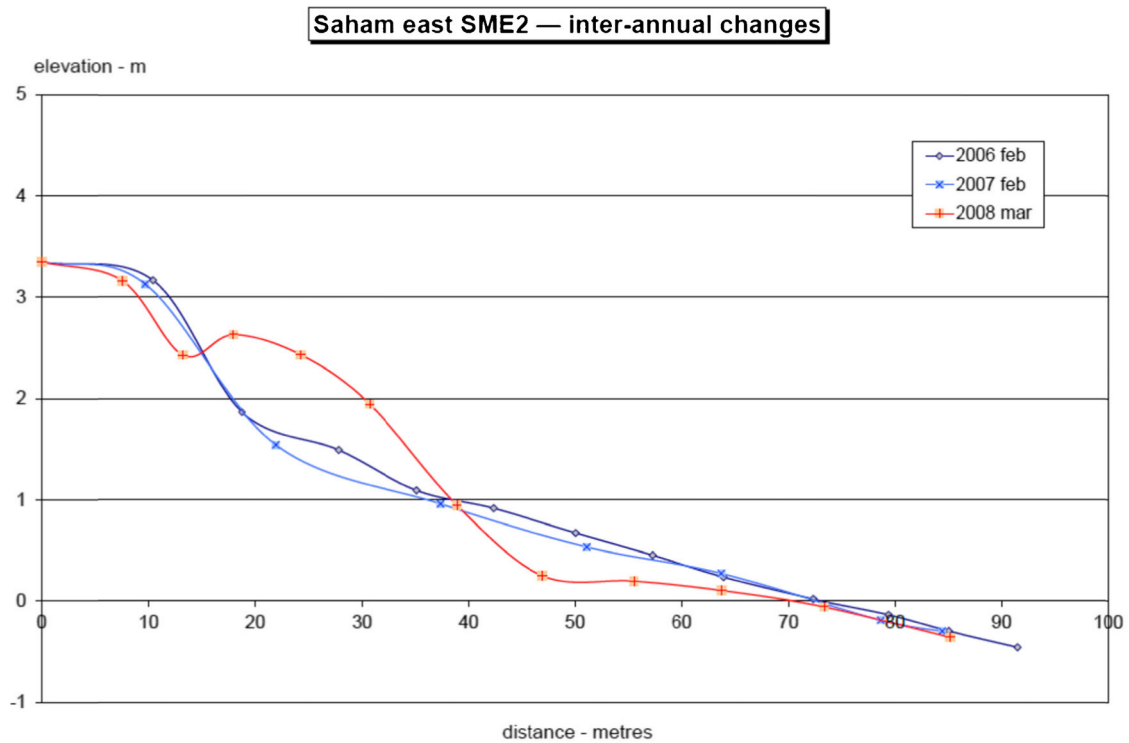


Fig. 8 Plot of survey profile showing inter-annual and seasonal changes at lines SME2 located on the SE part of Saham fishing harbor. There was accretion in the middle slope in March 2008 than the other years. Accretion was observed in November 2006 compared to the other seasons

development projects, which were prevalent in Al Batinah. Retreat of up to 0.6 m/year was recorded. The report projected that, without any remedial action, Al Batinah

would lose many of its excellent beaches within the following 10 to 30 years. From profile surveys conducted north and south of Sohar Port, Atkins Consultants Ltd

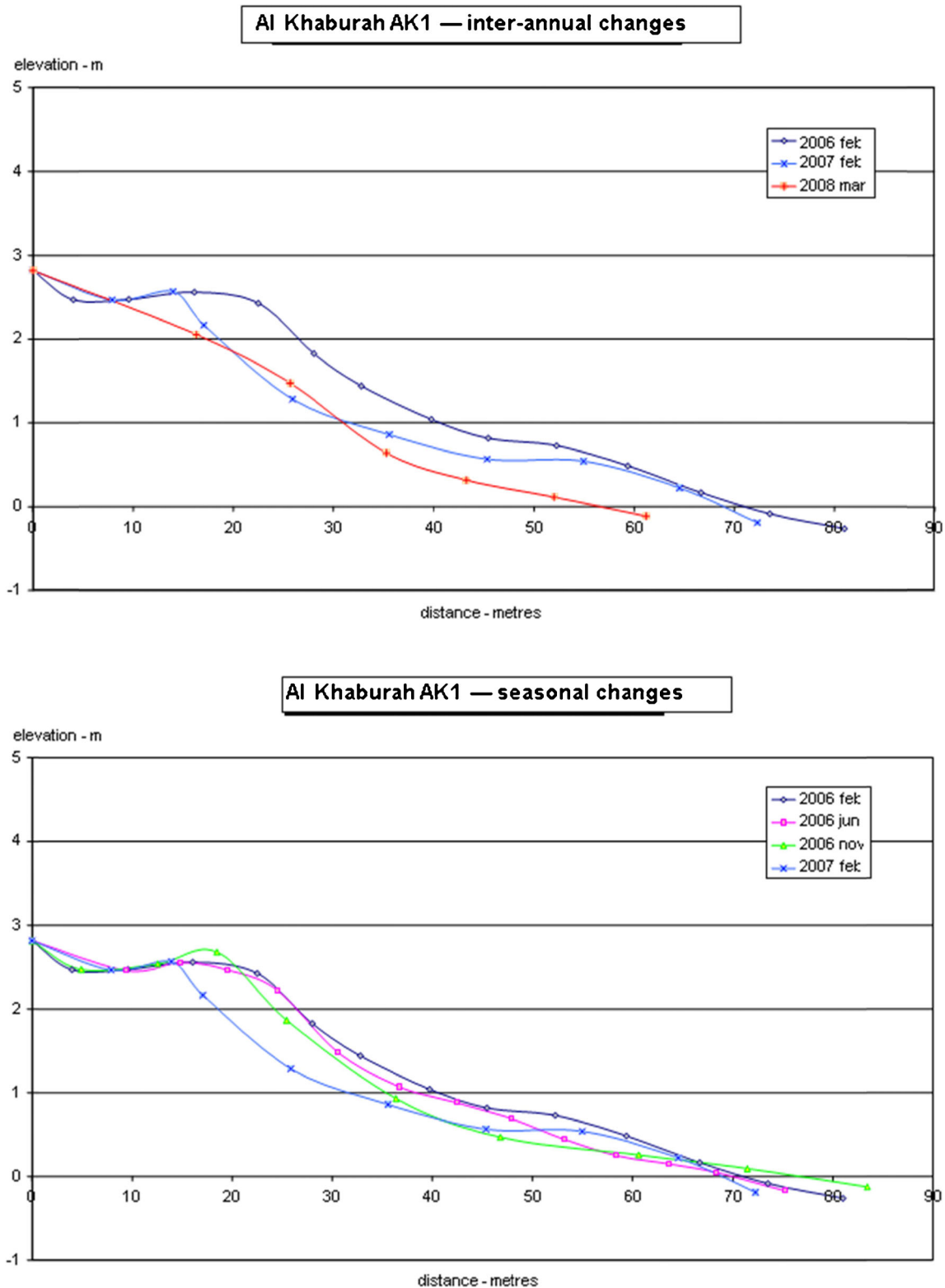


Fig. 9 Plot of inter-annual and seasonal changes at line AK1, located closest to Wadi Hawasnah in Al Khaburah. Water retention and recharge dam has been constructed on Wadi Hawasnah resulting in limited

sediment reaching the coast. The upper plot shows erosion in March 2008 compared to the other years. The season plot shows erosion in February 2006 compared to the other seasons

(2001) observed sediment accretion of up to 2 m south of the breakwater, toward Majis jetty, which was constructed as part

of the port development. Beach erosion of approximately 1 m was recorded north of the northern breakwater arm. The study

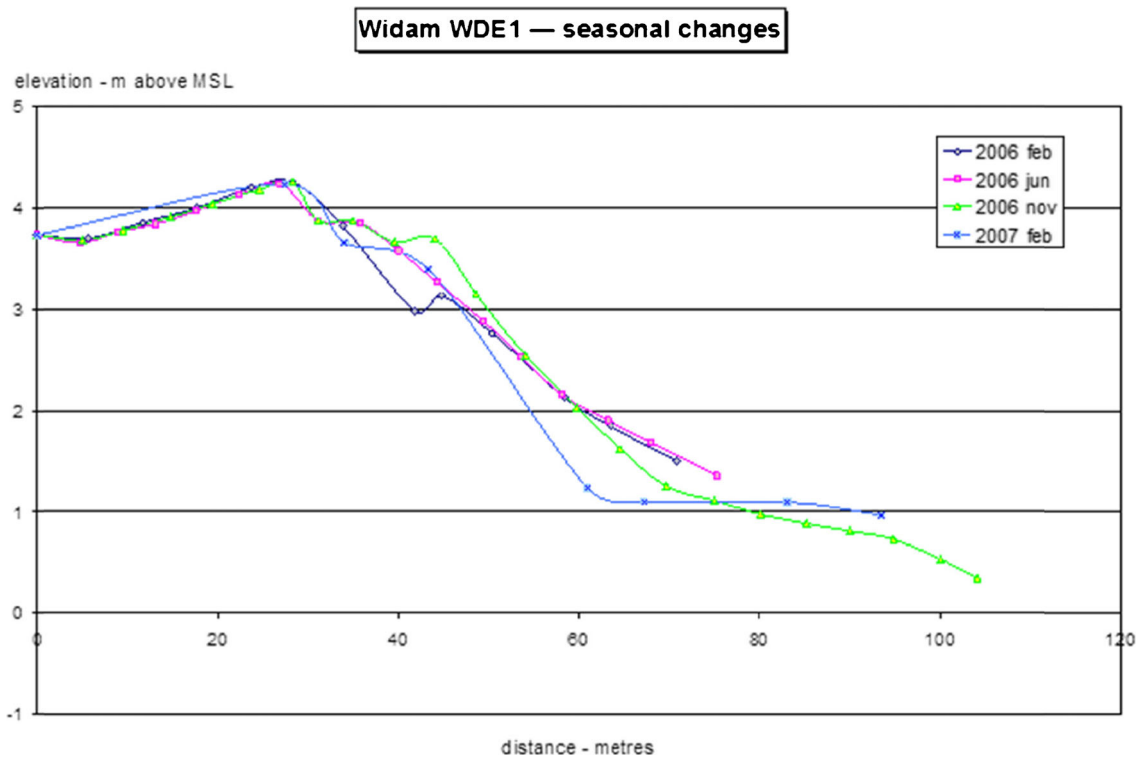
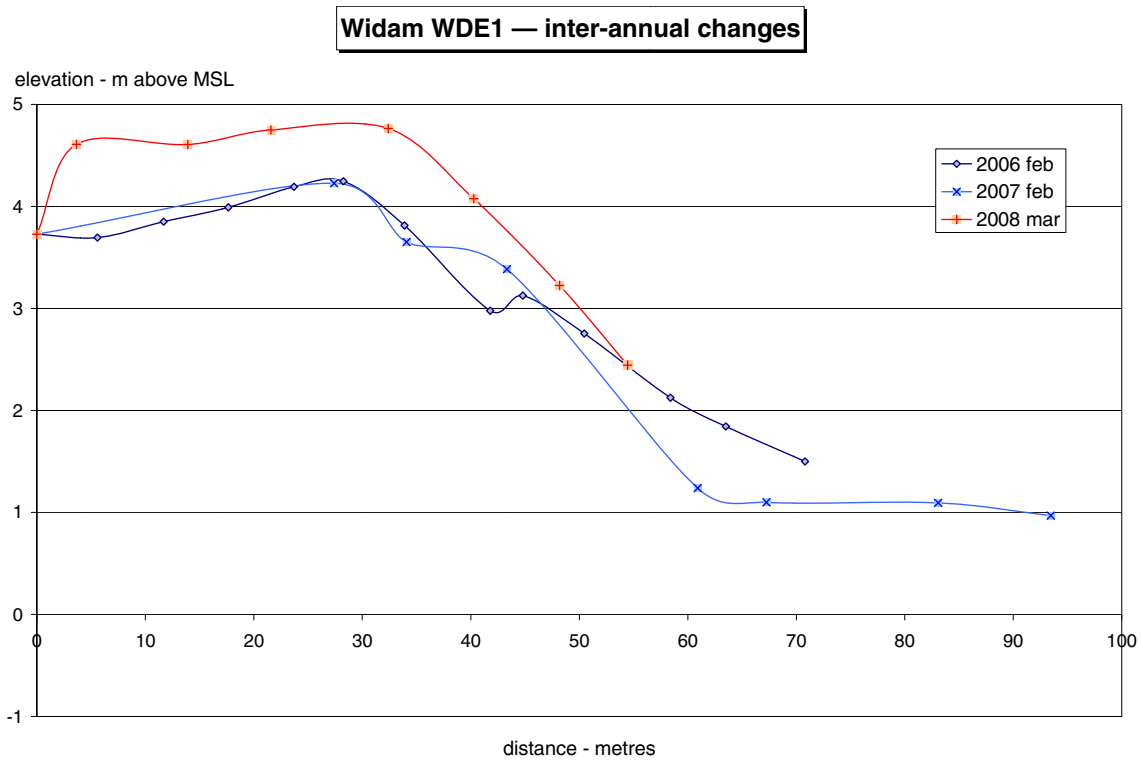


Fig. 10 Plot of inter-annual and seasonal changes at WDE1 located on the on SE of Royal Navy of Oman harbor and the village of Widam Sahel. Accretion is observed at this site. There was seasonal accretion in November 2006 and erosion in February 2006

did not consider such erosional levels catastrophic and, therefore, did not recommend any immediate coastal engineering

mitigation measures for the nearby village of Harmul. Badenhorst (1995) considered Al Batinah to be in a state of

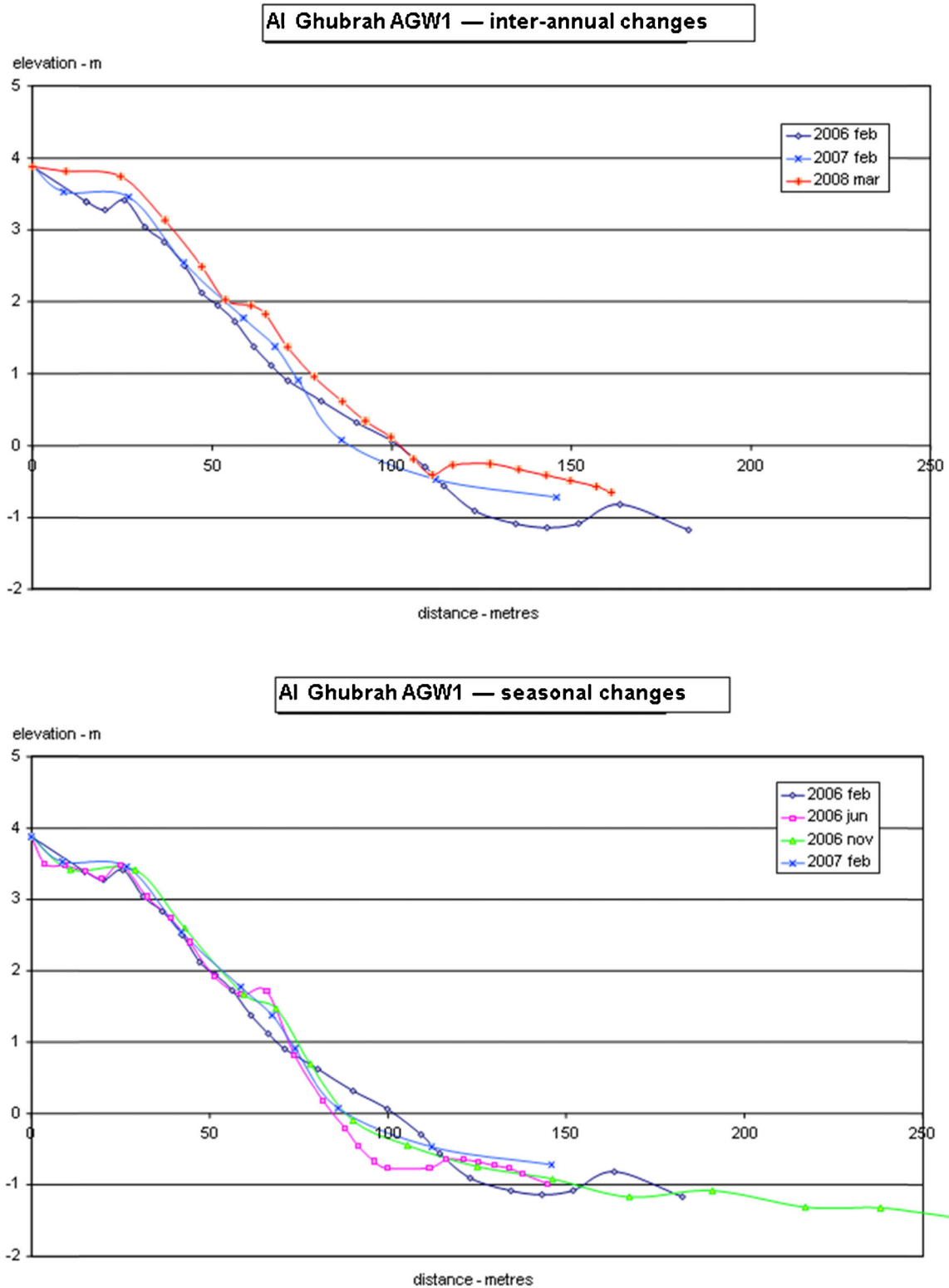


Fig. 11 Plot of inter-annual and seasonal change at line AGW1, located NW of Al Ghubrah desalination plant. The inter-annual plot shows more accretion in 2008 than 2007 and 2006. Erosion is observed in the lower slope of survey conducted in June 2006

widespread erosion with recharge dams, coastal instability, sea level rise, and harbor construction all being possible causes. He recommended collating existing data, developing a

setback line and preparing a coastal management plan. He concluded that the widespread occurrence of erosion along Al Batinah suggested that the phenomenon may not be

related to the construction of harbors or other engineering structures.

Erosion and accretion patterns of adjacent lines for a site were similar. However, in general, there was much small-scale variability at all the sites. From this study, the sites that showed consistent inter-annual erosion were as follows:

- Lines HR1 and HR2, Harmul—Erosion took place at these sites, west of the newly constructed Sohar Port.
- Lines HSW4 and HSW2, Sohar Souk—Erosion took place at these sites, west of the new Sohar fishing harbor.
- Line AK1, Al Khaburah—Erosion occurred at this site, at the mouth of Wadi Al Hawasnah. Presumably, the delta formed by sediments deposited by the wadi is being slowly eroded.

Lines BRW3 and BRW2 at Barka showed consistent accretion linked to natural processes from 2007 to 2008. This is most likely due to sediment input from a wadi that carried sediment to the coast during the floods resulting from cyclone Gonu.

In general, the erosion/accretion in 2006–2007 was much less than in 2007–2008, implying that the rates may vary yearly depending on climate and other conditions. The effects from cyclones, such as Gonu, could have a stronger imprint compared to other years. Such conditions have been observed by Park and Edge (2011) in the shoreline of the SE coast of Texas where most severe erosion and seaward transportation of sediments occur during major storms. Previous coastal erosion monitoring studies in Al Batinah were conducted within about 36 months. It is obvious that a comprehensive monitoring for several years will be needed to make very definite conclusions. The erosion and accretion rates observed in this study are in agreement with previous studies which recorded erosion and accretion rates between 0.6 m/year to 2 m/year (James Dobbin Associate Inc 1992; Atkins Consultants Ltd. 2002). Previous studies were only restricted to a small part of Al Batinah coast. This study was confined to monitoring the erosion and accretion rates on the NW and SE of major engineering structures along the whole of the Al Batinah coast. This study also included some information on seasonal erosion changes.

The sediment transport rates along the Omani coast are estimated at around 88,000 to 100,000 m³/year in a northwesterly direction between Widam and the United Arab Emirates border (Hayes and Baird 1993; McCue 2005). Although about 48 % of natural sediment supply is trapped by recharge dams, the remaining portion of about 52 % or 811,200 m³/year is about eight to nine times the sediment transport rate along the coast. Although the overall balance at this point indicates an abundance of sediment supply with respect to sediment removal rates, two important points have to be taken into account. The first point is the local effect of these dams. It seems

that the areas which are most affected by erosion are those near the outfall of these dammed wadis, such as As Seeb, Barka, Al Khaburah, and Sohar. The second point is that as more recharge dams are constructed in the future as part of the country's water resources development plan, care should be taken not to greatly reduce sediment supplies below the transport rates. More importantly, it is not advisable to concentrate the construction of dams on adjacent wadis that supply sediments over long stretches of the coast as that could exacerbate the local erosion problem.

Conclusions

Beach erosion/accretion in Al Batinah was investigated by conducting repeated beach profile surveys at selected locations along the coast. The objective was to monitor potential erosion/accretion on the SE and NW of major engineering structures such as harbors and desalination plants. Surveys were conducted five times between February 2006 and February–March 2008 using a total station. The more detailed studies of beach profiles, although hampered by the loss of some benchmarks and profiles, broadly came to the conclusion that the soft shoreline of Al Batinah coast was fairly stable. Most profiles showed some variability, but overall, there was stability over the 24 months of monitoring. About one quarter of the profiles showed a little local accretion and slightly fewer showed limited local erosion. The cases of accretion or erosion were all closely associated with harbor and other coastal engineering structures, and no cases were extreme. The maximum erosion rates measured in this study was 0.8 m/year implying that the area is not undergoing major erosion. Field visits indicated that erosion of the upper beach zone was often due to roadways or corniches being constructed on fill on the upper beach zone, whereas in the natural situation, waves are still active. Hence, wave erosion of the fill deposited in the upper beach zone now takes place at these sites.

Tropical cyclone Gonu, which struck Oman on June 4, 2007, affected only a small part of the study areas and the waves were not particularly large. However, the accretion measured at the affected areas near to Barka was more than double the rates before the cyclone. Beach profiles of February–March 2008 were measured 9 months after Gonu. Considerable recovery from offshore movement of beach sediments due to storm waves seems to be the case at the affected sites. There could be some contribution or modification in the longshore drift and hence erosion and accretion patterns on Al Batinah coast from the construction of major engineering structures as well as water retention dams. However, it is likely that the most severely eroded areas and major sediment transport in Al Batinah coast occurred during major storms. It is critical to acquire erosion and other geomorphic

measurements at selected areas immediately after a major storm such as tropical cyclones Gonu and Phet which affected Oman in 2007 and 2009, respectively.

Al Batinah coast will become increasingly important as a population center and an agricultural and industrial area, so human impacts on the coast will increase. It is therefore vitally important to practice sound coastal zone management in this area. Essential for this is a knowledge of key processes controlling sediment budgets and for regular monitoring of shoreline response. Capacity building in these research areas and in coastal zone management in general is critical. The precautionary principle should apply to any proposed development in the coastal zone; unless absolutely necessary (e.g., when building a harbor), any roads, houses, etc. must be built well away from the storm line. The distance of traditional villages away from the storm line is a safe setback line, having been determined from many years' experience. This distance is typically about 15 m. Only temporary structures like fisherman's sheds could be built closer. In areas where erosion has been experienced due to the construction of new harbors, an additional setback distance must be used. The two main areas where this is happening are (i) west of the new large Sohar Industrial Port, at Sohar Souk, and (ii) Harmul, west of the new fishing harbor at Sohar. To increase the efficiency and reduce potential errors, future studies should utilize real-time kinematics (RTK) from satellite-based positioning systems as GPS, GLOSASS, and Galileo in conjunction with high-resolution digital elevation model (DEM) for the continuous assessment of beach erosion along the whole Al Batinah coast.

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