What can long-term *in situ* monitoring data tell us about our coastlines?

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Abstract

Long-term *in situ* monitoring of beach morphology is indispensable for capturing the processes of foreshore morphological changes, and thus many beach monitoring campaigns have been conducted globally. Here, we review the various foreshore beach processes attributable to cross-shore sediment transport, which have been elucidated through long-term beach monitoring. Historical *in situ* beach monitoring has revealed many daily–annual-scale cyclic foreshore beach morphological changes and shoreline changes; however, many shorter- and longer-term processes remain unresolved, for example, the short-term response to tidal fluctuations and the long-term response to sea level rise. The cost per area surveyed of state-of-the-art equipment will gradually decrease over time, and the accuracy, resolution, and volume of information obtained from the monitoring methods, which are still in the early stages of development, will improve as research progresses. Continued long-term monitoring and acquisition of previously unmeasured monitoring data through the development of monitoring methods are expected to help elucidate unresolved beach processes.

Impact statement

Beaches play an important role in disaster prevention by reducing the wave energy reaching land and protecting hinterlands from wave overtopping and other hazards. Using various methods, scientists have monitored beach morphology to investigate how and by what mechanism beach morphology changes. For example, long-term *in situ* monitoring data of beach morphology, obtained using methods such as leveling and satellite-based positioning, have provided insight into beach morphological processes on various time scales. Temporary erosion caused by storms and cyclic morphological changes caused by seasonal wave fluctuations have been well studied; however, certain processes, such as the effects of tidal and wave interactions on beach morphological change and the response to sea level rise, remain unresolved. High-quality multisite monitoring data acquired by new surveying methods, such as drones and LiDAR (light detection and ranging), will provide clues that will help elucidate these processes.

Introduction

Sandy beach morphology is changed continuously by waves, currents, and winds. The variability of beach morphology is one of the important processes in geophysics, and knowledge of the underlying processes is important for coastal disaster prevention. The foreshore, that is, the swash zone, is the area that changes most dynamically in response to the wave regime. Erosion of the foreshore can lead to large-scale shoreline retreat; therefore, foreshore morphology should be monitored carefully from the perspective of coastal management. To capture the processes underlying foreshore morphological change, *in situ* monitoring data of beach morphology are indispensable, and thus many beach monitoring campaigns have been performed worldwide.

Monitoring of beach morphology, including not only the foreshore but also the upper shoreface (i.e., the surf zone and shallower than the wave base), is mandatory in investigating foreshore morphological changes. Especially for long-term beach processes such as shoreline change due to sea level rise (SLR) and sediment transport caused by extreme storms once every few decades, the sediment transport and deposition processes between the lower and upper shoreface cannot be ignored (Anthony and Aagaard, 2020; Harley et al., 2022). Most beach monitoring campaigns focus on the backshore to upper shoreface zone, while the lower shoreface is rarely monitored adequately.

Campaigns for monitoring beach morphology can be divided broadly into two categories. The first is short-term and high-frequency or high-resolution monitoring, which mainly focuses on the morphological changes caused by cross-shore sediment transport. We call such campaigns concentrated monitoring. The monitoring usually involves a single or a limited number of cross-shore transects, and the beach profile is measured to reveal the changes that occur over a period of a few days to a few weeks during storm and calm wave conditions. Short-term monitoring campaigns often target foreshore morphological changes that are substantial even over short

periods. Generally, in such monitoring campaigns, beach profiles are measured using leveling, RTK-GNSS (real-time kinematic global navigation satellite system) (Harley et al., 2011a), and more recently, LiDAR techniques (Almeida et al., 2013; O'Dea et al., 2019; Phillips et al., 2019).

The second category is long-term and low-frequency or low-resolution monitoring, which focuses on morphological changes caused by both cross-shore and longshore sediment transport. The monitoring usually involves obtaining a shoreline position of the entire coast and extensive three-dimensional bathymetry. Morphological changes due to beach rotation (Klein et al., 2002) and quantitative imbalance of longshore sediment transport around jetties, which can occur coastwide on monthly–multiyear scales, can be obtained. In a situation where external factors such as the wave regime or the sediment supply from a river could change on annual–decadal scales (Warrick et al., 2015; Nguyen and Takewaka, 2022), the object of monitoring might be to determine the long-term morphological changes due to cross-shore and longshore sediment transport. In some cases, such as in the Netherlands, a national strategy has promoted continued long-term annual monitoring of beach profiles on the national scale (i.e., the Jarkus program; e.g., Southgate, 2011). Satellite imagery and aerial photos are often used to observe long-term shoreline changes (Crowell et al., 1991; Luijendijk et al., 2018), and camera measurements such as Argus are also used to analyze short-term variations (Holman et al., 1993; Harley and Kinsela, 2022). Single-beam sonar and more recently narrow multibeam sonar mounted on boats are generally used to produce precise bathymetric maps over large areas (Barnard et al., 2011), although the frequency of such monitoring is often as low as once per year.

On the basis of the above, it would be pertinent to ask whether there are any long-term high-frequency observations that could fill the gap between the two types of monitoring campaign. The answer to that question would be yes. Long-term and high-frequency monitoring is also important. Even though wave conditions might not change over long periods of time, beaches often show long-period fluctuations in morphology, suggesting that the nonlinearity of short-period beach responses could drive long-term beach changes. However, the nonlinearity is so small that limited short-term high-frequency observations cannot fully reveal the underlying processes. Here, we summarize the relation between the monitoring cost per unit area, and the accuracy and resolution (or volume of information) of each monitoring method (Figure 1). The latest technologies such as airborne LiDAR and multibeam sonar combined with GNSS can provide large volumes of high-quality data with high accuracy; however, they are unsuitable for long-term high-frequency monitoring campaigns owing to their high operational costs. Conversely, satellite imagery and Argus photos are low cost and are suitable for long-term observations. However, the information obtained from such images is often limited to shoreline position, and the temporal or spatial resolution is not always adequate. Positioned between the two in Figure 1, RTK-GNSS, leveling, and single-beam sonar attached to a jet ski are techniques unsuitable for monitoring of large areas, but they can be used to obtain high-accuracy data over a limited area. These methods can be used for long-term high-frequency observations if certain costs are borne. Recently, automatic observations of the zone from dunes to the foreshore have been obtained by fixed LiDAR and photogrammetry using UAVs (unmanned aerial vehicles) (Turner et al., 2016), which represents a recent major development in beach monitoring with reduced costs and improved accuracy, although
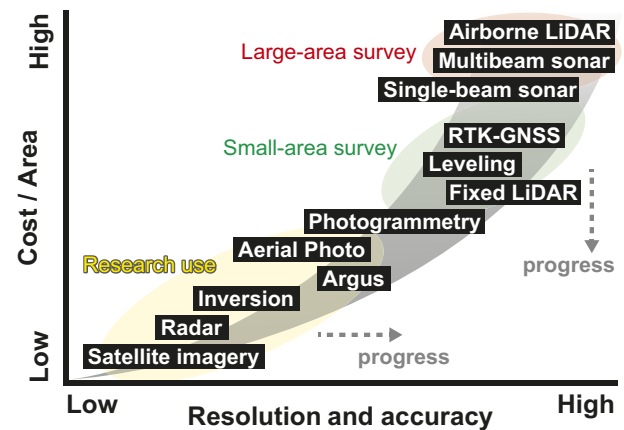

Figure 1. Relationship between cost and information of beach survey methods.

challenges remain with regard to surveying underwater areas. There is no doubt that long-term, high-frequency, and high-resolution *in situ* monitoring of beach morphology can be realized only at great cost. Consequently, long-term beach profile monitoring campaigns are very limited worldwide owing to the constraints of human and financial resources.

Representative beach monitoring campaigns that have obtained relatively high-frequency (i.e., more than bimonthly) beach profiles for more than 15 years have been conducted at Narrabeen, Australia (Short and Trenbanis, 2004; Harley et al., 2011a; Turner et al., 2016), Moruya, Australia (Thom and Hall, 1991; McLean and Shen, 2006; Tamura et al., 2019), Hasaki, Japan (Banno et al., 2020), Omotehama, Japan (Kato et al., 2013), Duck, USA (Lippmann and Holman, 1990; Larson and Kraus, 1994; Nicholls et al., 1998), Torrey Pines, USA (Ludka et al., 2019), Ocean Beach, USA (Yates et al., 2011; Splinter et al., 2014), Truc Vert, France (Castelle et al., 2020), and Porsmilin, France (Bertin et al., 2022). In these long-term *in situ* monitoring campaigns, beach profiles along one or several limited transects are measured using techniques such as GNSS. Although the depths and elevations of the offshore and landward boundaries vary among campaigns, most of the monitoring campaigns at least cover the foreshore area. Long-term campaigns that have been conducted bimonthly (or more frequently), which include various beach morphological changes such as abrupt large erosion during periods of high waves and gradual accretion during periods of low waves, provide very valuable information. Based on such monitoring data, numerical models have been developed to reproduce the morphological changes of the foreshore, and associated beach morphological change processes have been investigated. In this paper, we review the various foreshore beach processes that operate on multiple time scales due to cross-shore sediment transport that have been elucidated through long-term beach monitoring, and we discuss the scientific knowledge that we can expect to obtain in the future through further development of techniques for monitoring beach morphology and continued long-term monitoring campaigns.

In studies on foreshore morphological changes, cross-shore position with a specific elevation is often used as a proxy for beach morphology (Boak and Turner, 2005). It is called the shoreline position and is defined with a specific elevation, such as the height of mean high-water springs (MHWS), which retreats during erosion and advances during accretion. When the morphological change of an entire foreshore is targeted, multiple reference heights

are used for shoreline positions. Thus, shoreline changes and foreshore morphological changes are almost synonymous in terms of the definition.

Cyclic foreshore beach processes revealed by observations

The usefulness of long-term high-frequency monitoring data is highlighted in periodicity analyses of short-term (less than 1 year) foreshore morphological changes. Spectral analysis revealed cyclic shoreline changes with 1-year and 6-month cycles at Hasaki, Japan (Banno and Kuriyama, 2020), which are caused by cross-shore sediment transport related to seasonal fluctuations in waves (Eichentopf et al., 2020). Conversely, data recorded at Narrabeen, where high-frequency morphological changes have also been monitored, showed no clear seasonal variation in the mean shoreline position (Lazarus et al., 2019). This is probably attributable to the fact that the incident wave energy at Narrabeen does not show clear cyclic variation, such as a 1-year cycle, and because of the relatively large influence of morphological changes induced by longshore sediment transport such as beach rotation (Harley et al., 2011b; Harley et al., 2015) associated with seasonal changes in the direction of incoming waves. In the case of substantial impacts such as longshore sediment transport and sediment budget changes, the importance of long-term high-frequency monitoring data increases because large volumes of data are required for statistical extraction of the morphological changes caused by cross-shore sediment transport.

A recent study using a large volume of monitoring data revealed a foreshore beach process previously masked by variations in other factors. The process is affected by tidal fluctuations. The study revealed that a large tidal range during spring tides and king tides (Flick, 2016) makes erosion of the upper swash zone more likely, even within the same wave regime (Banno and Kuriyama, 2020). Several monitoring studies showed that beach elevation of a few meters above the mean water level was minimal a few days after the spring tide (LaFond, 1939; Aubrey et al., 1976; Clarke et al., 1984). However, the effect of the primary underlying beach process could not be distinguished from other effects, such as waves, because of limited available data and thus full explanation of the beach process was not proposed. In relation to this process induced by tidal fluctuations, sediment transport and the morphological changes even between a single tide, that is, between rising and falling tides, might be affected by infiltration and exfiltration of water on the beach face (Duncan, 1964; Clarke and Eliot, 1987; Butt et al., 2001; Masselink and Li, 2001; Coco et al., 2004). However, beach processes on the hourly scale have not yet been clarified because of lack of long-term morphological change data monitored at intervals of less than 1 day, for example, 6 h, which is the time scale of ebb and flood tides.

Daily–annual-scale foreshore beach processes revealed by observations

For time scales of less than 1 year, as shown by the seasonal cycle in the spectra of beach monitoring data, it has long been known that a shoreline will advance and retreat seasonally owing to seasonal wave fluctuations (e.g., Shepard, 1950). When waves are calm, sediment is transported onshore by sheet flow and accreted over a period of days. Conversely, when waves are large during storms, erosion can occur in just a few days (sometimes only a few hours) with sediment transported offshore via suspension. On many beaches, wave characteristics vary seasonally, and the foreshore accretes with a well-developed berm during seasons with frequent periods of calm waves and retreats with a relatively gradual slope during seasons with frequent periods of high waves.

Equilibrium-based shoreline change models are used widely to estimate short–long-term accretion and erosion, such as that over daily–multiyear periods including seasonal variation (Miller and Dean, 2004; Yates et al., 2009, 2011; Davidson et al., 2013; Turki et al., 2013; Castelle et al., 2014; Splinter et al., 2014; Banno et al., 2015; Jara et al., 2015; Dean and Houston, 2016; Vitousek et al., 2017; Lemos et al., 2018; Chataigner et al., 2020; D'Anna et al., 2020, 2021a, b; Montaño et al., 2020). A beach will approach a theoretical equilibrium profile, on which no further morphological change is caused, when subjected to the same wave regime for an extended period. Equilibrium-based shoreline change models are based on the concept of the equilibrium profile determined by waves. In such numerical models, shoreline change is determined by the imbalance of the actual position of the shoreline relative to the equilibrium shoreline position. The advantage of such models is that beaches where substantial erosion has already occurred will not experience further notable erosion (Eichentopf et al., 2020). Consequently, the long-term robustness of equilibrium-based shoreline change models is high because simulation results tend not to diverge unrealistically but fluctuate around the equilibrium shoreline position; thus, such models are often used for long-term hindcasts and forecasts.

Equilibrium-based shoreline change models have been used to reproduce shoreline changes over periods of several years relatively well (e.g., Yates et al., 2009; Splinter et al., 2014). The temporal resolution of the estimated shoreline changes depends largely on the monitoring data used to calibrate the model; therefore, in many cases, such simulations are limited to reproduction of only seasonal change. When using high-frequency beach monitoring data for calibration, such as the daily data obtained at Hasaki and the biweekly data acquired at Narrabeen, short-term erosion over a period of a few days can be estimated (e.g., Davidson et al., 2013; Splinter et al., 2014; Banno et al., 2015).

Even when using high-frequency shoreline change data for calibration, the estimated temporal resolution might not always be high depending on the tuning of the model parameters (Montaño et al., 2020). Parameter tuning can be classified into two methods: minimizing the error with respect to the observed shoreline position and minimizing the error with respect to the amount of shoreline change. In most studies, the former method is adopted because it is most likely to reduce the overall error; however, it tends to reproduce trends without reproducing fine-scale high-resolution temporal variation. The latter method is more likely to reproduce short-term variations, but it does not account for shoreline position errors; consequently, the resulting output of estimated shoreline positions might differ substantially from the measured shoreline positions. We have not found any studies that even discuss the above calibration methods, even though selection of the method adopted depends on the purpose for which the model will be used.

Annual–decadal-scale foreshore beach processes revealed by observations

Beach morphological changes over long time scales are often discussed in the context of global climate change. Using long-term beach monitoring data, coastal responses to atmospheric and oceanic variations such as the El Niño–Southern Oscillation (ENSO), which varies on the scale of a few years, have been investigated (Barnard et al., 2015). Beach morphological monitoring data along 48 coasts of

the Pacific Rim revealed different responses to the impact of ENSO in different locations. For example, erosion is greater along the California coast (e.g., Ocean Beach) and Japanese coast (e.g., Hasaki) facing the Pacific Ocean in winter when El Niño events occur, while erosion is greater in Australia (e.g., Narrabeen) in winter when La Niña events occur. It has been suggested that the impact on erosion is caused by waves and sea level variations affected by ENSO. Relationships between atmospheric and oceanic variations and waves have been indicated by the high correlation of atmospheric pressure patterns and climate indices with the variations of waves (Castelle et al., 2017; Kishimoto et al., 2017), which consequently also influence shoreline variations (Kuriyama et al., 2012; Robinet et al., 2016). Studies at Hasaki (Kuriyama et al., 2012) and Truc Vert (Robinet et al., 2016) showed that 45% and 70% of long-term shoreline variability can be explained by teleconnections of large-scale atmospheric and oceanic variability, respectively. Another study reported that the 18.6-year nodal tidal cycle causes shoreline retreat (Gratiot et al., 2008); however, the response of beach morphological change to long-term sea level change with such periodicity has not yet been fully investigated using a sufficient volume of long-term monitoring data.

The Bruun rule (Bruun, 1962), which determines the probable amount of future shoreline retreat associated with a shift of the equilibrium beach profile with SLR, is widely used. In terms of the concept, a rising sea level is expected to cause foreshore erosion and offshore sediment transport near the foreshore. It has been highlighted that this method enforces many assumptions (Cooper and Pilkey, 2004) and is susceptible to the setting of parameters such as closure depth (Udo et al., 2020) and that it might not always match actual morphological changes (Ranasinghe et al., 2012). In historical beach monitoring data, the effect of SLR per unit time on cross-shore sediment transport is very small in comparison with the morphological changes caused by wave variations and longshore sediment transport. Therefore, the validity of the Bruun rule and the details of actual coastal response to SLR remain unknown. The effects of SLR on beach morphological changes are currently being investigated in laboratory experiments that simulate SLR as close as possible to actual scale, while controlling all other external forces (Atkinson et al., 2018; Atkinson and Baldock, 2020), and in analysis of shoreline changes exposed to hypothetical SLR where land subsidence is important (Nguyen and Takewaka, 2020). The current solution is to couple the Bruun rule with an equilibrium-based shoreline change model. Long-term shoreline predictions have been simulated using this approach by incorporating the shoreline retreat predicted by the Bruun rule (Vitousek et al., 2017; D'Anna et al., 2020, 2021a), and by introducing the Bruun rule directly into the term representing the equilibrium shoreline position in the model (Banno et al., 2015; D'Anna et al., 2021b).

Long-term shoreline changes are also expected to occur in response to long-term changes in wave climate. Therefore, it is important to determine whether we reproduce long-term shoreline change on annual–decadal scales using equilibrium-based shoreline change models. A recent study using multiple equilibrium-based shoreline change models hindcasted shoreline change over 15 years and predicted blind shoreline change over 3 years for Tairua beach, New Zealand (Montaño et al., 2020). Long-term hindcasts (past 22 years) and scenario projections (future 88 years) of shoreline change have been calculated for Hasaki, Japan (Banno and Kuriyama, 2014; Banno et al., 2015). In both studies, the observed long-term shoreline variability (type of long-term trend) could not be reproduced adequately, leading to deterioration of the overall reproduction accuracy (i.e., R^2 and RMSE (root-mean-square error)). Whether this observed long-term shoreline variation is caused by wave climate change or by other processes remains a matter of debate, but current shoreline change models are limited in terms of their skill in reproducing and predicting long-term shoreline variation. In forecasting applications, equilibrium-based shoreline change models use unique parameters determined from observational data. Thus, the simulated shoreline position tends to be near the mean shoreline position, and reproducibility and prediction skill are diminished when forced with nonstationary wave conditions over time (Ibaceta et al., 2020), such as wave climate changes due to global warming. It has also been suggested that beach response could be affected in the long-term by substantial erosion due to extreme storms (Kuriyama and Yanagishima, 2018). Although foreshore morphological change is also affected by the effects of wave breaking by longshore bars (Kuriyama and Banno, 2016), which move and develop on a multi-year scale (Ruessink et al., 2003, 2007), these effects are not introduced into equilibrium-based shoreline change models. In practice, there is a dilemma regarding incorporation of the effects of longshore bars into shoreline change models because prediction of longshore bars has yet to be fully accomplished. Although process-based models such as XBeach (Roelvink et al., 2009) and DELFT3D (Lesser et al., 2004), which include calculations of wave deformation and dissipation, are effective in simulating detailed coastal processes, producing long-term forecasts over periods of more than a few months remains challenging (Hanson et al., 2003). Nevertheless, application of process-based models to long-term forecasting has been studied (Davidson, 2021). An approach to long-term forecasting in response to wave fluctuations and SLR, which combines a process-based model and a probabilistic method, has also been studied (Ranasinghe et al., 2012; Dastgheib et al., 2022). Currently, a reasonable simple solution is to account for the uncertainties in hindcasts and forecasts by Monte Carlo simulations (Banno and Kuriyama, 2014) or by ensembles of multiple models (Montaño et al., 2020). Original wave monitoring and prediction data also contain uncertainty, and the uncertainty of wave data should be considered, for example, using Monte Carlo simulations (Chataigner et al., 2022) or ensembles of wave conditions (Vitousek et al., 2021).

As described above, reasonably adequate knowledge of foreshore morphological changes on time scales of a few days to a few years has been obtained from long-term beach monitoring data. However, we need further monitoring data to investigate foreshore morphological changes on time scales shorter than a day and longer than several years.

Monitoring future

The development of monitoring methods will provide new insights into beach morphological changes and processes. The cost per surveyed area of state-of-the-art equipment such as LiDAR will gradually decrease through technological innovation and more efficient manufacturing, and the accuracy, resolution, and volume of information obtained from monitoring method using satellite imagery and Argus photos will improve as research progresses. In recent years, miniaturized LiDAR scanners that can be mounted on UAVs have reduced the cost of using large airborne platforms. Efficient collection of beach morphological data by combining sonar with autonomous underwater vehicles and other remotely operated vehicles is also expected to be adopted for long-term monitoring in the future. Additionally, estimation of bathymetry using satellite techniques, such as synthetic aperture radar imagery (Pleskachevsky et al., 2011; Capo et al., 2014) and inverse estimation of bathymetry from video recordings of waves (Matsuba and

Sato, 2018), have recently been investigated, and the resolution and accuracy of such approaches will improve over coming years. It is expected that long-term ultra-high-frequency monitoring data will become more readily available in the future following these developments, and we anticipate that easier acquisition of such data will allow enhanced monitoring of beach morphology.

For example, if beach profiles were observed over a long period at intervals of several hours using automatic instruments such as LiDAR with a green laser (e.g., Pastol, 2011), it might be possible to quantify the effects of tides on beach morphological changes during flood and ebb tides, as suggested by Phillips et al. (2019) and Banno and Kuriyama (2020). Moreover, XBeach (Roelvink et al., 2009), which is used mainly to simulate short-term morphological changes, could be used to consider the effects of wave run-up infiltration and groundwater effluent on the morphological changes of sandy beaches, expanding on previous work that used XBeach to study similar effects on gravel beaches (XBeach-G; McCall et al., 2015). Elucidation of detailed processes through high-frequency beach monitoring could greatly advance these modeling efforts, potentially improving not only the reproducibility of short-term morphological changes, but also the reproducibility of long-term morphological changes that represent the integration of the former.

Considering the risk of coastal disasters, temporary erosion following a single storm event should also be estimated in addition to estimation of seasonal shoreline variations. Therefore, it is necessary to increase the temporal resolution of shoreline changes estimated by models using monitoring data with the highest possible temporal resolution. Moreover, if long-term observation data with high temporal resolution were available for many beaches, the practicality of research on shoreline prediction would be greatly enhanced. One of the future developments of equilibrium-based shoreline change models, through application with as much beach monitoring data as possible, will be to accumulate knowledge to permit generalization of the model parameters that are currently estimated site-specifically for each beach where monitoring data are available. For example, the relationship between sediment grain size and model parameters might also lead to generalization of model parameters (Yates et al., 2011; Splinter et al., 2014), which would allow prediction of short-term erosion on beaches where monitoring data are not necessarily abundant.

Together with improved data quality (increase in data acquisition frequency, resolution, and volume of information) and quantity (increase in the number of beaches monitored), it is also essential that long-term morphological data continue to be obtained. We need long-term monitoring data of beach morphological change on beaches where SLR is significant to distinguish the effects of SLR on morphological changes from complex beach morphological changes caused by various other factors such as waves. We will experience a clearer and more extreme beach response to ongoing dynamic SLR and changes in wave climate in coming decades. With the monitoring data expected to be obtained in the future, we will be able to rapidly advance verification of the Bruun rule, which has currently been discussed only as a concept, and elucidation of long-term factors and processes of beach fluctuation that are not yet fully understood.

Conclusions

This paper broadly summarized the findings of foreshore morphological change through historical long-term and high-frequency monitoring of beach profiles. Morphological changes on the time scale of a few days to a few years can now be reproduced by equilibrium-based shoreline change models using waves as the driving force, which has been achieved thorough the availability of monitoring data and extensive study in recent years. However, because of lack of beach monitoring, we still do not have sufficient knowledge of the morphological changes that occur over periods shorter than a day, which might be affected by tides, and those that occur over periods of a decade, which are closely related to SLR and wave climate changes. Recently, data acquired during several long-term beach monitoring campaigns, for example, that at Narrabeen (Turner et al., 2016), have been released to the public under the concept of open data (Ludka et al., 2019; Castelle et al., 2020; Bertin et al., 2022). It is expected that more and more beach monitoring data will become available in the future, and that the use of open data will greatly advance our understanding of foreshore beach processes. Long-term and high-frequency monitoring of beach morphological changes is also expected to be conducted for more beaches following the development of monitoring methods. As larger volumes of monitoring data become available for use in future studies, we expect not only improvement of physics-based models, but also marked development of statistical models, such as deep neural networks, which have progressed remarkably in recent years (Goldstein et al., 2019). Through various studies using monitoring data, we expect to gain more comprehensive understanding of beach processes on various time scales, resulting in development of prediction technology for beach morphological changes with high accuracy and high certainty that will help in the effort to maintain long-term beach stability and durability.

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