University of Groningen

Tracked to protect - Spatiotemporal dynamics of recreational boating in sensitive marine natural areas

Meijles, E. W.; Daams, M. N.; Ens, B. J.; Heslinga, J. H.; Sijtsma, F. J.

Published in:
Applied Geography

DOI:
10.1016/j.apgeog.2021.102441

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2021

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Meijles, E. W., Daams, M. N., Ens, B. J., Heslinga, J. H., & Sijtsma, F. J. (2021). Tracked to protect - Spatiotemporal dynamics of recreational boating in sensitive marine natural areas. *Applied Geography*, *130*, [102441]. https://doi.org/10.1016/j.apgeog.2021.102441

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Applied Geography 130 (2021) 102441

Contents lists available at ScienceDirect

Applied Geography

journal homepage: http://www.elsevier.com/locate/apgeog

Tracked to protect - Spatiotemporal dynamics of recreational boating in sensitive marine natural areas

E.W. Meijles[a,*], M.N. Daams[a], B.J. Ens[b], J.H. Heslinga[c], F.J. Sijtsma[a]

[a] *Faculty of Spatial Sciences, University of Groningen, P.O. Box 800, 9700 AV, Groningen, the Netherlands*
[b] *Sovon-Texel, Sovon Dutch Centre for Field Ornithology, 1790 AB, Den Burg, the Netherlands*
[c] *European Tourism Futures Institute, NHL Stenden University of Applied Sciences, Rengerslaan 8, 8917 DD, Leeuwarden, the Netherlands*

ARTICLE INFO

Keywords:
Automatic identification system (AIS)
GPS tracking
Big data analysis
Wadden sea
Sustainable landscape management
UNESCO Natural world heritage site

ABSTRACT

In many coastal areas, high numbers of recreationists may exceed ecological capacities. Careful monitoring of visitor flows is a first prerequisite for coastal area management. We show how AIS ship data can be translated into interpretable information on recreational boats and investigate whether AIS can provide monitoring information when compared to nature conservation policy targets. In the Wadden Sea UNESCO World Heritage Site we used nearly 9 million data points to create spatiotemporal patterns for the 2018 recreation season. We combined this with shipping lanes and bathymetry data and compared the resulting patterns with nature protection regulations. Our results show that most of the traffic is concentrated around tidal channels. We also show that exceeding speed limits is not predominant behaviour, but the effect of speeding on birds and seals might be more severe than the data suggests. We mapped favourite tidal flat moor activities, and observed where this occurs in Marine Protected Areas. We conclude that AIS analysis can provide valuable recreational boating monitoring, relevant to sensitive coastal area management in the entire Dutch Wadden Sea for the full recreational season. Broader integration of AIS with radar data and ecological data can add to the power of using AIS.

1. Introduction

In many coastal areas, recreation and tourism have become major economic factors worldwide over the last century, providing income and jobs to touristic destinations (Davenport & Davenport, 2006; Libosada, 2009; Wesley & Pforr, 2010). Especially those forms of recreation that are based on experiencing nature, landscape and natural heritage have become increasingly popular (Newsome et al., 2013). However, the positive impact of tourism is not solely economic. Tourism is also an opportunity for nature protection through creating awareness, public support and funding for nature protection (Libosada, 2009; McCool & Spenceley, 2014). At the same time, the extent and type of tourism and recreation may reduce the ecological quality of protected and vulnerable landscapes (Buckley, 2012). Multifunctional use of national parks may create conflicts because high numbers of recreationists may exceed ecological capacities (e.g. Hadwen et al., 2007; Lyon et al., 2011; Schlacher et al., 2013; Wimpey & Marion, 2011). Human disturbance is a major threat to colonial seabirds worldwide (Croxall et al., 2012) and coastal birds are especially vulnerable (e.g. Liley & Sutherland, 2007; Steven & Castley, 2013). Furthermore, different types of recreational activities may have a negative impact on recreational behaviour of others (Orellana, 2012).

This means, that when striving after a sustainable landscape, management of (national) natural parks needs to balance economic, environmental, recreational, and social values (Geneletti & Van Duren, 2008; Meijles et al., 2014). Consequently, natural park managers need not only have data on ecological quality, but also need information on the spatiotemporal behaviour of visitors relative to sensitive areas (Meijles et al., 2014). For the same purpose, there is a need to understand which landscape and infrastructural characteristics are preferred by visitors (Pouwels et al., 2020; Stamberger et al., 2018) and how this differs between activities (e.g. Beeco, Hallo, et al., 2013). Location-specific data on visitor flows, stop places, use of facilities, activities or other recreational hotspots can be used to define and steer away from sensitive protected zones (Dye & Shaw, 2007; Wolf et al., 2012). Location information of visitor flows can be used to route visitors to a wider or narrowed down range of locations avoiding overcrowding, to better match visitor's interests (Freuler & Hunziker, 2007; Lyon et al.,

---

* Corresponding author.
E-mail addresses: e.w.meijles@rug.nl (E.W. Meijles), m.n.daams@rug.nl (M.N. Daams), bruno.ens@sovon.nl (B.J. Ens), jasper.heslinga@nhlstenden.com (J.H. Heslinga), f.j.sijtsma@rug.nl (F.J. Sijtsma).

https://doi.org/10.1016/j.apgeog.2021.102441
Received 4 June 2020; Received in revised form 19 March 2021; Accepted 22 March 2021

2011; Lyon et al., 2011, 2011; Orellana et al., 2012; O'Connor et al., 2005) or to increase effectiveness of patrolling nature park rangers.

Traditional methods for estimating visitor flows include visitor surveys (with or without mental mapping), space-time diaries and self-mapping (Hallo et al., 2012), interviews, direct observations (i.e., physically following visitors) and checkpoint monitoring (Van Marwijk, 2009; Wolf et al., 2012; Xiao-Ting and Bi-Hu (2012). As the costs of GPS devices have lowered and are widely available in smartphones, empirical data using GPS has been added as a well-proven method (Korpilo et al., 2017; Meijles et al., 2014; Shoval & Isaacson, 2007). GPS data result in detailed track logs of followed routes with high spatial and temporal resolutions, which extended the possibilities in following larger groups of respondents than traditional methods (Meijles et al., 2014). It is important to keep in mind that data may be biased, as visitors aware of their GPS device could change their spatiotemporal behaviour (O'Connor et al., 2005; Taczanowska et al., 2008) and that there may also be privacy issues associated with this type of research (Van den Bemt et al., 2018).

Because of the development of GPS-based monitoring methods during the past decades, spatial movement analysis has rapidly developed (Long & Robertson, 2018), and knowledge on tourist mobility in natural areas has increased (Chantre-Astaiza et al., 2019; Korpilo et al., 2017; Lera et al., 2017; Wolf et al., 2012). There is a large body of literature in the ecological, tourism and geographical domains relating the spatio-temporal visitor patterns in natural areas to landscape composition (e.g. Stamberger et al., 2018; Van Marwijk, 2009), recreational preferences (e.g. Meijles et al., 2014; Pouwels et al., 2020), weather conditions (Sykes et al., 2020), accessibility through main roads and car parks (e.g. Beunen et al., 2008), network connectivity within the natural area (e.g. Taczanowska et al., 2014) and special attractions (e.g. Beeco, Huang, et al., 2013; Hallo et al., 2012).

However, most of these studies focus on terrestrial natural areas, and although there are many publications on the influence of recreational behaviour on ecological values in marine coastal areas (e.g. Davenport & Davenport, 2006; Schlager et al., 2013), the use of GPS-based visitor tracking in marine natural areas is limited (e.g. Parrot et al., 2011). Spatiotemporal analysis in such environments is often solely focussed on safety (e.g. Silveira et al., 2013), shows a limited temporal cover (Balaguer et al., 2011) or is mostly restricted to the terrestrial section of coastal areas (e.g., Smallwood et al., 2012). This is surprising since over 500.000 ships at sea in over 140 countries use Automatic Identification System (AIS), a tracking system that uses GPS receivers, VHF transceivers and other navigation sensors to show and transmit their live location (IMO, 2019). The system is designed for helping skippers and maritime authorities, mainly for safety purposes. The system can be used passively (only receiving) or actively (receiving and transmitting). Terrestrial AIS base stations along coastlines can track and log the ship's signals (Deter et al., 2017). International ships over 300 gross tonnage and all passenger ships, irrespective of size, are legally required to use AIS (IMO, 2019). Although recreational skippers are encouraged to use AIS actively for safety reasons, they not legally required to do so if they stay under an, often regionally differing, maximum ship size (Deter et al., 2017).

The lack of detailed marine spatiotemporal visitor studies hampers the sustainable management of ecologically valuable marine landscapes. Therefore, this paper focuses on assessing spatiotemporal recreation patterns in an ecologically sensitive marine landscape. Our case study area is the UNESCO World Heritage Dutch Wadden Sea area. We aim to (1) develop a method to transform raw AIS data into easily interpretable information on visitor flows and to (2) investigate whether AIS can provide insightful visitor monitoring information on intensity of use.

2. Wadden Sea area

2.1. Natural values

For its globally unique geological and ecological values, the Wadden Sea (Fig. 1) is listed by UNESCO as Natural World Heritage Site in 2009 (UNESCO, 2009). The World Heritage Site encompasses the international Wadden Sea of Denmark, Germany and The Netherlands. In the Netherlands it is narrowly defined, including the tidal sea with its intertidal sand and mud flats, and the summer polders and undiked salt marshes surrounding the sea, while the diked mainland and islands are excluded from the Heritage Site (Sijtsma et al., 2019). The sea is rather shallow, with dry tidal flats during low tide and depths of the natural channels ranging from less than 5 m to deeper than 30 m between the islands (Elias, 2017, p. 51). In 2016, the Wadden Sea was elected by the Dutch general public as the most beautiful natural area of the Netherlands (Dutch Government, 2016). Millions of birds depend on the Wadden Sea (Fig. 1) for foraging, breeding, moulting, and migrating. Some bird species use the area for a short period, whereas others stay for a longer period and forage in the area to gain enough energy for further migration. Some birds spend the entire winter in the area (Kloepper et al., 2017). The salt marshes, tidal flats and sublittoral areas provide a high availability of food to large numbers of migratory birds, including 43 protected species under the Natura 2000 regime. Around 31 species of ground-breeding birds are found in the area, mainly breeding on the islands. The birds are susceptible to natural and human disturbances during feeding, moulting and roosting (Kleefstra et al., 2011; Kloepper et al., 2017).

The area is home to healthy populations of two seal species, the harbour seal (*Phoca vitulina*) shows increasing numbers since the mid-1900s and the grey seal (*Halichoerus grypus*) since the 1970s. The area functions as reproduction area for the harbour seal in summer and for the grey seal in winter. They also forage in the area and rest on the edges of the tidal flats at low tide. Seals run the risk of being disturbed by people coming close during low tide at haul-out sites and in periods when females are suckling young.

2.2. Tourism and recreation in the study area

Because of the widespread recognition of its ecological qualities and scenic landscapes, the Wadden Sea area has become very attractive to tourists and tourism has become the dominant economic activity (Heslinga et al., 2018; Sijtsma et al., 2012; Revier, 2013). Whilst most tourist activities take place at the islands (Sijtsma et al., 2012), many marine activities also take place within the UNESCO World Heritage Site (Sijtsma et al., 2019). During their trips, recreationists undertake activities such as sailing, anchoring, mudflat hiking, looking for mussels/oysters, and seal and bird watching (Heslinga et al., 2019). One specific activity for this region is tidal flat mooring ('droogvallen' in Dutch), in which flat-bottomed boats anchor at high tide and wait until the tide recedes (Fig. 2). At low tide, the boat rests on the tidal flats, providing the opportunity to get off board and to go for a stroll in the surroundings.

The monitoring of tourism is reasonably well established in the area through sluice and harbour counts providing long-term visitor numbers since the 1980s and a policy programme is in place to combine tourism and nature protection in a sustainable way (Tjaden et al., 2018). However, the area thus far has not used AIS data to create detailed spatio-temporal patterns of recreational ships at landscape scale for the full tourist season as a baseline assessment for recreational pressure on ecological values. Therefore, the region is a relevant case for researching spatiotemporal dynamics of recreation in sensitive marine natural areas.

2.3. Rules and regulations

To protect natural values in the area, several rules and regulations

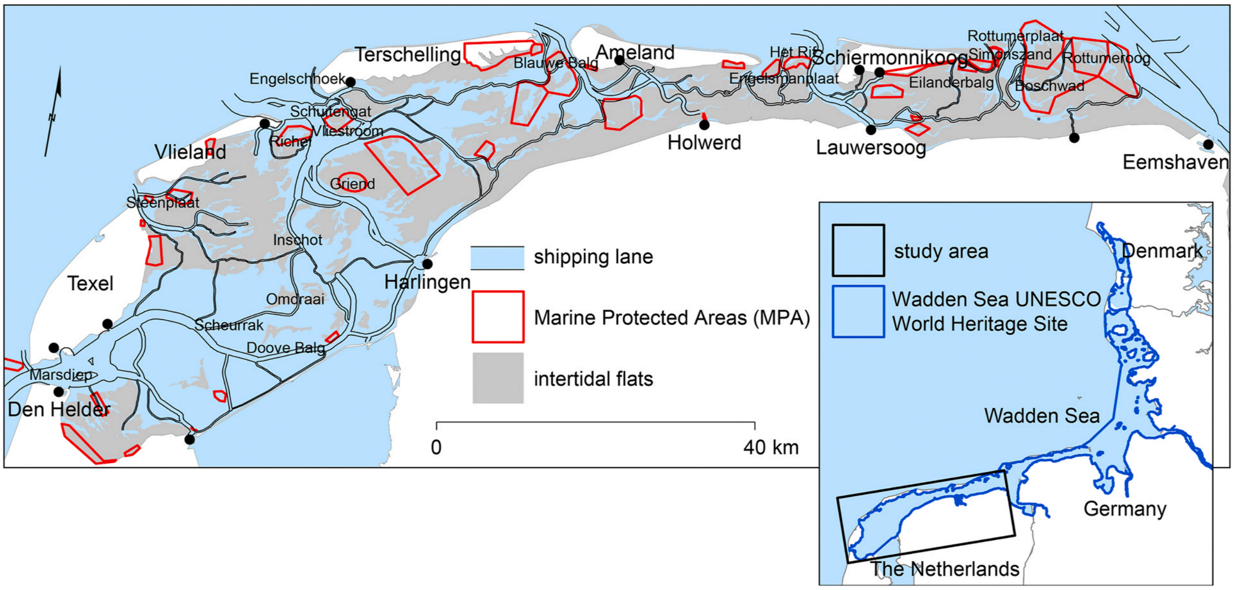

Fig. 1. Map of the study area, showing the tidal sea with the intertidal flats, shipping lanes and Marine Protected Areas (MPAs). The inset shows the location of the study area relative to the Wadden Sea UNESCO World Heritage Site.

Fig. 2. Sailing ship during tidal flat mooring, a typical recreation activity in the Wadden Sea (Photo: Meijles, 2019, on the tidal flats near Inschot).

are in place. In the Dutch sector of the Wadden Sea, Marine Protected Areas (MPAs) are designated by law. These areas are closed for shipping and visitors because of high nature values. Some of the MPAs are closed throughout the sailing season, others only a part of the year (i.e. during the nesting or moulting season). In some cases, access is allowed at high water, but not at low tide. In most areas, the beginning and end of the closure period is fixed, whereas in other areas ‘dynamic closure’ regulations apply, i.e. closing off is determined based on ecological indicators. MPAs are indicated on marine maps.

There are also strict rules on speeding. The maximum sailing speed is set at 20 km/h, except for a few shipping lanes where no speed limit applies. In addition, visitors are actively encouraged to behave according to the code of conduct, which describes a set of rules and guidelines, which have been mutually agreed upon by recreational boaters themselves, to ensure experiencing the natural values does not harm the area.

The law enforcement is the somewhat complex responsibility of municipalities, provinces, and the Dutch government. The WaddenUnit patrols the area with a number of inspection ships and acts on behalf of the Dutch Ministry of Agriculture, Nature and Food Quality. Several nature management organisations such as State Forestry Service, Natuurmonumenten and It Fryske Gea are patrolling in specific natural sites within the study area, such as Griend, Engelsmanplaat, Rottumerplaat, and Rottumeroog.

3. Methodology

3.1. *Approach*

We used high-resolution AIS data of recreational ships to create spatiotemporal patterns for the recreation season May–September 2018. We combined the resulting maps with spatially explicit landscape data, such as natural channels, shipping lanes, bathymetry, and tidal data (Table 1). In addition, we compared the resulting patterns with rules and regulations and with ecological indicators to assess to what extent natural values could be threatened.

3.2. *Data sources and data preparation*

3.2.1. *AIS*

AIS data is stored by Rijkswaterstaat, the executive agency of the Dutch Ministry of Infrastructure and Water Management. In principle, all incoming AIS signals are stored in the central database, but in the event of heavy shipping traffic, AIS data from larger commercial shipping traffic will take precedence over others such as smaller recreational ships, which means that occasionally not all data will be saved (De

Table 1
Available datasets with their format, source and spatiotemporal resolution.

Title	Data type	Estimated spatial resolution	Temporal scale	Source
AIS	point	10 m	1 min	Rijkswaterstaat
Bathymetry	raster	20 m	multi annual	Rijkswaterstaat
Tidal flats	raster	20 m	annual	Rijkswaterstaat
Water depth	raster	20 m	1 min	InterTides
Shipping lanes	polygon	Scale 1:10,000	annual	Rijkswaterstaat
Tidal channels	polygon	Scale 1:10,000	multi annual	Rijkswaterstaat
Buoys	point	Scale 1:1,000	irregular	Nautin
MPAs	polygon	Scale 1:10,000	multi annual	Rijkswaterstaat

Vreeze, 2018, pers. comm.). The signals are captured as data points, which consist of GPS-based geographic coordinates (latitude-longitude) of ships with a 1-min time interval, ensuring a high spatiotemporal resolution of the data. A unique ship identifier, ship type (e.g. fisheries or motor yacht), time (UCT), speed over ground, bearing, ship type, and the draught of the ship are also stored (Silveira et al., 2013). To maintain the privacy of individual ships and their users for this research project, the Maritime Research Institute Netherlands (MARIN) anonymised all ships, which means that all formally assigned identifiers were replaced by new, randomised identifiers. We have used the international AIS coding for selecting recreational traffic. AIS code 36 represent sailing ships, code 37 represents pleasure craft (for personal use). Within the AIS code 60–69 (passenger ships) we have made a distinction between ferries and other passenger traffic based on the spatial behaviour. We identified the main ferries by visually selecting the frequently returning ships in the major ports and set them apart to be able to separate between ferries and other recreational passenger ships. Smaller ferry services (such as between the islands Texel and Vlieland; see Fig. 1) were kept and therefore remain in the category passenger ships. In case of missing or invalid codes (AIS code 99), the AIS records were removed from the database.

Subsequently, we applied several filters to the AIS database. We removed all AIS datapoints outside of the study area, defined by the spatial extent of the Wadden Sea Long Term Ecosystem Research (WaLTER) project (WaLTER, 2020), which delineation follows the Dutch Wadden Sea area's coastline, slightly extending to a narrow strip into the North Sea. To mitigate the influence of possible noisy GPS-signals or GPS systems that were turned on while boats were stored on land, we also filtered terrestrial AIS data points. Furthermore, as our analysis focused on the spatial behaviour of recreation activities on open water, AIS data points from within-port locations were also removed.

We also identified outliers in the AIS database (referred to as 'drift' by Xiao-Ting & Bi-Hu, 2012). These were defined as 'logged points that were distinctively separated from their predecessors and/or successors in the track log' (Meijles et al., 2014, p. 50). In practice this means, that if consecutive AIS locations at 1-min intervals are separated by improbable large distances (i.e. kilometres), the outlier was removed. See also Meijles et al. (2014) for this approach.

Some speed records showed unrealistically high values or were set to zero. We have therefore recalculated all speed values based on the Euclidian distance of consecutive records and the time interval. In the case of reappearing unrealistically high speeds, we assumed the AIS data point locations were erroneous and were consequently removed from the database.

Since many ships do not have draught measuring equipment on board, or do not have linked them with AIS equipment (De Vreeze, 2018, pers. comm.), we interpreted the draught data in the AIS database to be unreliable. Instead, we have created this by combining location, time, tide and bathymetry data from the InterTides model (Sections 4.2.4 and 4.2.5).

3.2.2. *Tidal channels and shipping lanes*

Most shipping lanes in the Dutch Wadden Sea follow the natural tidal channels. They are indicated at sea by navigation buoys. When the channels shift due to natural processes, the buoys are relocated by Rijkswaterstaat. The channels and buoys are digitally stored in a national geodatabase, in which maximum speed of each shipping lane are stored as attribute data. In areas where natural erosion and sedimentation processes in the channels is high, buoys are relocated more frequently than updated in the database (Sybren, 2019, pers. comm.). We have therefore manually adjusted the channel data to the most recent circumstances based on open data of buoy locations provided by Nautin, a not-for-profit organisation providing nautical information for pleasure craft including individual observations of users on buoys and channels (Nautin, 2020).

3.2.3. *Marine Protected Areas (MPAs)*

Marine Protected Areas (MPA) are areas that are closed for shipping and visitors because of high natural values (See Section 3.3). The geographical delimitation of the areas may deviate from year to year since the tidal flats are dynamic. The coordinates of the MPAs are represented in a geodatabase managed by Rijkswaterstaat, but these are not always completely up to date with the situation in the field. In addition, the delimitation in the field determines the prohibited area and not the coordinates in the spatial database on the geoportal (WaddenUnit, 2019, pers. comm.). When interpreting the AIS data, differences between the geodata and the situation in the field need to be considered.

3.2.4. *Bathymetry*

Two datasets are available for bathymetry (WaLTER, 2020). One dataset is a simplified geographic vector representation of tidal flats at average low tide, which we use for visualization purposes. The second dataset is a raster file representing the depth of the seabed for both the littoral and sublittoral parts with a spatial resolution of 20 m. The data originally is produced by Rijkswaterstaat who update new subsections of the Wadden Sea annually (Elias & Wang, 2013, p. 76). In some areas, the dynamic nature of the tidal flats makes the dataset slightly out of date. From field observations, these areas may concern Het Rif, Eilanderbalg, Simonszand and the western side of Rottumerplaat. We discuss this in the results and conclusions sections where it is applicable.

3.2.5. *Spatiotemporal tide data (InterTides)*

For the shallow Wadden Sea, it is crucial to understand the difference in spatiotemporal behaviour of recreational ships during high and low tide situations. We have used the spatiotemporal InterTides model, which interpolates the water level at each location at any given moment based on 15 tidal gauge stations along the Wadden Sea at a temporal resolution of 10 min and a spatial resolution of 20 m (Rappoldt et al., 2014). By subtracting water level by depth from the bathymetry model, water depth could be determined for any place and at any time.

3.3. Spatiotemporal data analysis

3.3.1. Spatial distribution patterns of recreational traffic

Our analysis of spatial distribution patterns of recreational traffic was based on AIS data with a point density algorithm in a GIS environment (ArcGIS and Stata). This algorithm counts the number of AIS data points around each output raster cell, using a 25 m resolution and a 100 m search radius from the centre of the output raster cell. The resulting count was then divided by the search area (expressed in hectares), and thus provided a density of AIS data points per hectare. Grid cells with a high value represent areas visited by many ships; grid cells with low values are much less visited. By displaying these maps with a stretched classification based on standard deviations, variation in the map was optimised. By using different subpopulations, such as ship type, tide, the recreational season or a specific day, the spatial variability of recreational boating was mapped.

3.3.2. Tidal conditions

To analyse the spatially varying conditions of the tide, we carried out point density functions for low and high tide conditions. We have approached this by defining water level above average sea level as “6 h around high water” and the water level below as “6 h around low water”. We have defined high water as higher than 5 cm + NAP (Normaal Amsterdams Peil; average sea level in the Wadden Sea; Rijkswaterstaat, 2013).

3.3.3. Speed analysis

As for each AIS data point the speed was calculated (Section 4.2.1), we were able to assess the number of ships and their locations traveling at higher speeds than allowed. The lanes were buffered over a distance of 50 m to compensate for the dynamic nature of the natural channels (Section 4.2.2).

3.3.4. Tidal flat mooring

Tidal flat mooring was modelled based on the assumption that there is no water beneath the boat and the ship’s speed is zero. We used a point density analysis of the AIS data points in combination with water depth from the InterTides model (Rappoldt, 2014). If the water level of a ship as indicated by its AIS data point is lower than the bathymetry, the ship is potentially resting on the dry tidal flats. Because of possible interpolation errors in the tidal range and the bathymetry, we also used the ship’s speed. If the conditions of a water depth of 0 m and a speed value lower than 1.2 km/h (considering GPS measuring errors), we consider the boat to be mooring on the tidal flats.

4. Results

4.1. General traffic intensity

During the 2018 recreational season (May–September) in total 8,726,876 AIS data points were recorded in the Dutch section of the Wadden Sea after pre-processing (Section 3.2.1). About 48% of the data points were recorded passenger ships (7% ferries, 41% other passenger ships). 31% were sailing ships and the remaining 21% consisted of pleasure craft (Table 2). On average, sailing ships count 17,600 AIS data points per day, pleasure craft around 12,200 per day and passenger ships around 23,600 data points.

When plotting the number of AIS data points per day and plotted over time (Fig. 3), a substantial variation is shown. The spring and summer holidays (1–13 May and 7 July to 2 September, resp.) clearly show higher numbers of recreational traffic. On a shorter time-scale, the difference between weekend and weekdays is also visible, with higher numbers of sailing ships and pleasure craft in weekends than weekdays outside the summer holidays. Passenger ships show lower counts during weekend days in the summer holiday.

4.2. Hotspot analysis

Fig. 4 shows point density maps for different ship types. For each type, recreational patterns are geographically heterogeneous with most recreational shipping taking place in the main shipping lanes or natural channels. Commonly used channels are the main routes from the mainland (harbours at Den Helder, Harlingen Holwerd and Lauwersoog) to the islands. Other visible passenger ship journeys can be interpreted as tour boats, for example from Ameland to the tidal flats of the Blauwe Balg and from Lauwersoog to the tidal flats of Engelsmanplaat (seal watching). For the route from Lauwersoog to Rottumeroog, an uninhabited island high in natural values, a special permit is required. There are also many passenger ships at Schuitengat, probably visiting seal resting areas. The majority of the recreation traffic takes place in the western half of the Dutch Wadden Sea, which was also shown by Heslinga et al. (2019) based on survey analysis. Due to the nature of the shallow tidal sea, with tidal mud and sand flats intersected by deep natural gullies, the spatial patterns of sailing ships and pleasure craft are visually almost identical.

4.3. Out-of-channel behaviour

Fig. 5 and Table 2 show recreation point densities outside the shipping lanes. They indicate that most traffic is still in the immediate surroundings of the shipping lanes. Recreational traffic outside shipping lanes is around one third of the total recreational traffic but varies between the different types of ships. Since ferries have a relatively large draught, only a small proportion of ferry services (7%) sail outside the shipping lanes. Some ferries may be cutting off bends at high tide. Other passenger ships sail outside the channels substantially more often in 43% of the time, presumably to get close to tidal flats for seal watching. Pleasure craft and sailing ships show somewhat lower percentages (31 and 22% respectively), although it is physically no problem for small pleasure and sailing craft with a limited draught. Skippers often avoid larger or fast-moving commercial cargo, ferries and fishing ships by sailing out of the channels. In addition, many sailing ships use the still relatively deeper water surrounding the channels when navigating against the wind (Vroom, 2017, pers. comm.). There may also be some locational errors in the navigation channel database due to the dynamic nature of the tidal sea.

Table 2
General descriptives of AIS data points within and outside shipping lanes during the 2018 recreational season.

AIS code	ship type	AIS data points		AIS data points in shipping lane		AIS data points outside shipping lane	
		count	%	count	%	count	%
60–69	ferry	596,182	7%	555,819	93%	40,363	7%
	other passenger ship	3,611,268	41%	2,044,019	57%	1,567,249	43%
37	pleasure craft	1,855,231	21%	1,274,979	69%	580,252	31%
36	sailing ship	2,664,195	31%	2,078,097	78%	586,098	22%
	total	**8,726,876**		**5,952,914**	**68%**	**2,773,962**	**32%**

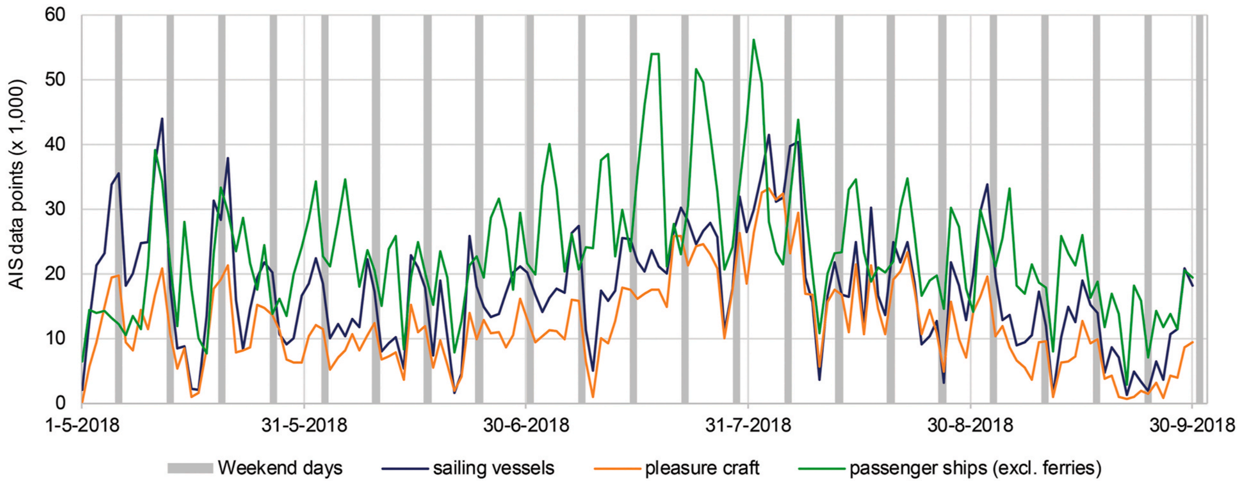

Fig. 3. AIS data counts for sailing ships, pleasure craft and passenger ships throughout the 2018 sailing season (May–September).

4.4. Spatial variability between tides

As the Wadden Sea is a tidal sea and therefore rather shallow, ships are mostly bound to the natural tidal channels. This is clearly visible in Fig. 6, where in both high and low tide conditions the shipping lanes show high AIS densities. At high tide, the typical water depth above the tidal flats is 1–2 m, which means that only ships with a limited draught and flat-bottomed ships can sail here and can only do this for a very short time. Ships regularly sail outside the shipping lanes between the islands of Texel and Vlieland and the mainland, and south of the island of Terschelling. During low tide, only the section of the Wadden Sea just north of the Afsluitdijk (Enclosure Dam) is deep enough for some traffic. Also, many small and narrow natural channels are hardly used, for example between the islands of Texel and Vlieland and through the Omdraai en Inschot. The channels south of the island of Schiermonnikoog are hardly used in both high and low tide conditions.

4.5. Exceeding speed limits

The speeding analysis show that overall, 6.5% of the AIS data points exceed 20 km/h (about 94,000 AIS data points), and around 1% of the AIS data points are registered in areas where this is not allowed (Table 3). Ferries generally sail at higher speeds around 40% of the time, with 2.3% of the data points showing high speeds where this is not allowed. Pleasure craft are sailing faster than 20 km/h almost 6% of the time, with 1.5% of the data points outside the allowed shipping lanes. The percentages are lower for sailing ships, since it is physically difficult to reach such speeds even considering tail tidal currents. In some cases, inaccurate GPS positions may cause speed overestimations.

We can conclude that percentage wise, the number of traffic movements faster than the maximum speed seems limited. On the other hand, passenger ships speeding has been recorded for 45,000 min and both sailing and pleasure craft combined totalled 35,000 min of speeding. To what extent this should be regarded as a threat to natural values needs yet to be determined.

Fig. 7 shows the spatial distribution of speeding based on a point density analysis. Speed limits were most often exceeded directly along the shipping lanes. Speeding by passenger ships and pleasure craft is predominantly observed in the Vliestroom, Inschot, Scheurrak and Omdraai shipping channels. Speeding also regularly occurs in the west-east channel directly south of the island of Ameland, where ships may cut corners. Some geometric errors in the GPS signals or the channel geodatabase may influence the results slightly.

4.6. Tidal flat mooring

For the point density maps of tidal flat mooring, we have increased the search radius from 100 to 500 m (Section 3.3.1), because we assume that people will regularly disembark during tidal flat mooring, which substantially increases the sphere of influence on natural values. Fig. 8 therefore acts as a measure for spatial influence on ecological factors. Table 4 shows that, percentage wise, tidal flat mooring appears to be limited. Passenger ships appear to be mooring on the tidal flats for 3% of the total recorded time. Although the Shipping Act prescribes for passenger ships that AIS devices must be permanently switched on, there are known cases where skippers disable AIS (WaddenUnit, 2019, pers. comm.) when tidal flat mooring. The figures presented here should therefore be interpreted as a minimum. For pleasure craft, tidal flat mooring occurs slightly more often with 4.1% of the AIS data points. For sailing yachts this is lower (1.8%), but in absolute numbers, these are much lower than for passenger ships. As this is a sample (not all ships in this category are obliged to use AIS actively), actual numbers will be higher for pleasure craft and sailing yachts. The spatial distribution (Fig. 8) shows popular tidal flat mooring locations south of the islands of Ameland, Schiermonnikoog and Griend and on the edges of the tidal flats of Engelsmanplaat and Richel.

4.7. Tidal flat mooring in MPAs

Although tidal flat mooring in MPAs during restricted periods is limited in respect to tidal flat mooring elsewhere (Table 4), we identified to what extent ships are in MPAs during closed periods. Table 5 shows a selection of the nine MPAs most visited for high and low tide situations. The full table can be found in the Supplementary Material online. Fig. 9 shows a low tide point density map of all tidal flat mooring locations during restricted periods. As a reference: if a single ship is tidal flat mooring, it is represented by at least 360 AIS data points (6 h) during the low tide period, unless the AIS equipment is switched off. Ships traveling through MPAs at high tide are typically represented by much fewer data points.

During the season as a whole around 32,000 (540 h) AIS data points were registered within MPAs during restricted periods. Of these, around 21% (111 h; 19 boats for a 6 h period) were registered as tidal flat mooring. Daily, this means that on average 212 min per day over the entire study areas was recorded. Tidal flat mooring intensities inside MPAs are considerably lower (38 AIS data points km^{-2}) than outside MPAs (152 km^{-2}).

The spatial distribution of tidal flat mooring is heterogeneous across

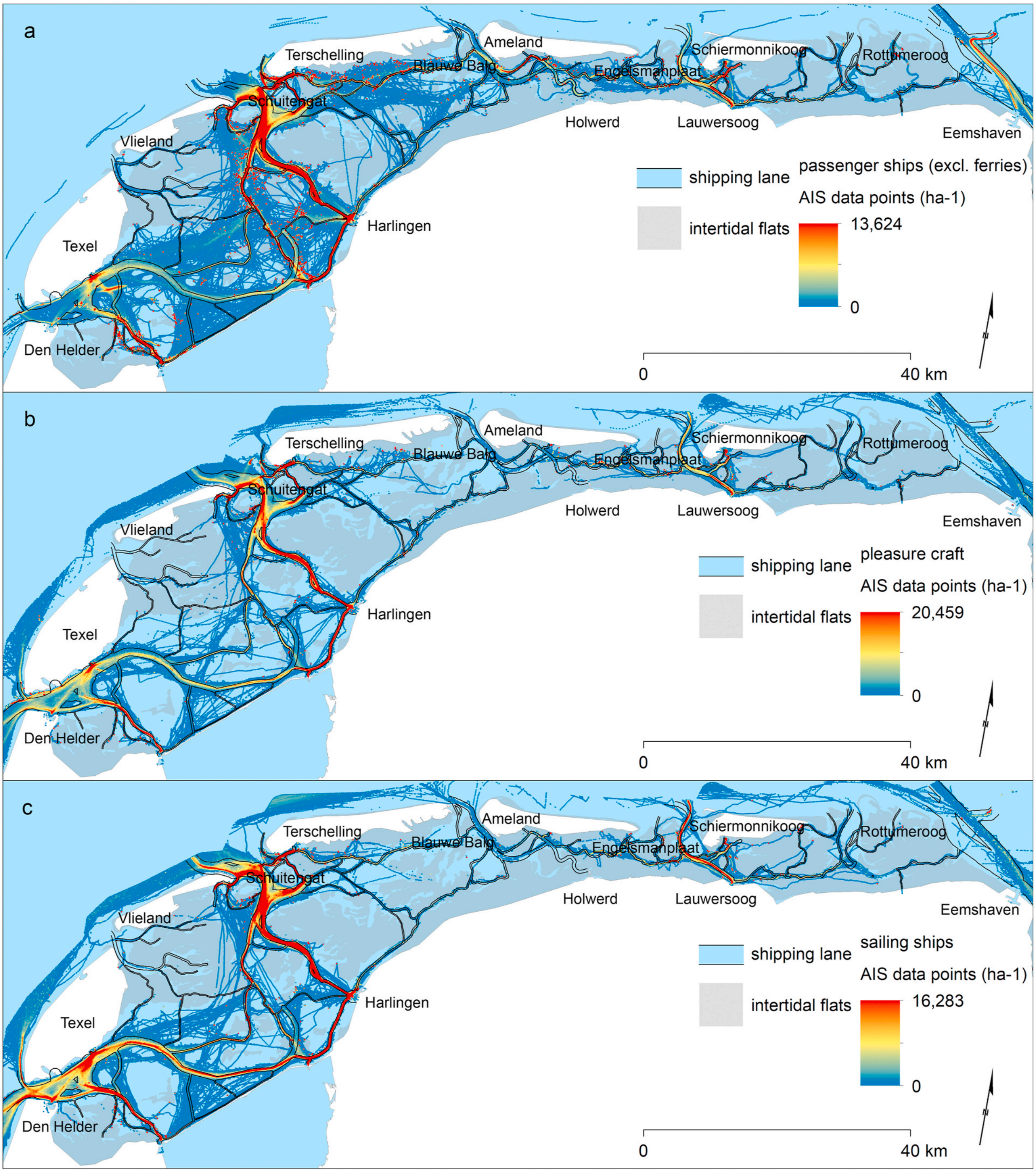

Fig. 4. Point density maps (recreational season 2018) with (a) passenger ships, (b) pleasure craft, and (c) sailing ships.

the tidal flats. The number of logged tidal flat mooring data points is lower in the western section than in the eastern parts of the Dutch Wadden Sea. The MPAs Boswad Schild Lauwerswal, Blauwe Balg Noord, Rottumeroog, Blauwe Balg Zuid, Richel and De Cocksdorp are visited relatively often. All ships actively carrying AIS are recorded here, irrespective of having any permits. To our knowledge, there are only two licensed passenger ships on the eastern Wadden to get to MPAs (Vroom, 2017, pers. comm.). Due to geomorphological dynamics, some MPA boundaries may have shifted meaning that there may be some errors in the AIS data point counts.

5. Discussion

5.1. Methodological enrichment

Visitor flow monitoring can use many methods (Van Marwijk, 2009; Wolf et al., 2012; Xiao-Ting & Bi-Hu, 2012), some more traditional, some more innovative (Korpilo et al., 2017; Van Marwijk, 2009). Although AIS is regularly applied to assess spatial and temporal distributions of ship activities, it is still a relatively under-used method (Kaiser & Narra, 2014) and mainly focuses on sea traffic safety (Silveira et al., 2013). With this paper, we add to the existing literature specifically focussing on recreation. We show that the globally available AIS data can be a useful tool to assess spatial recreational boating patterns in a

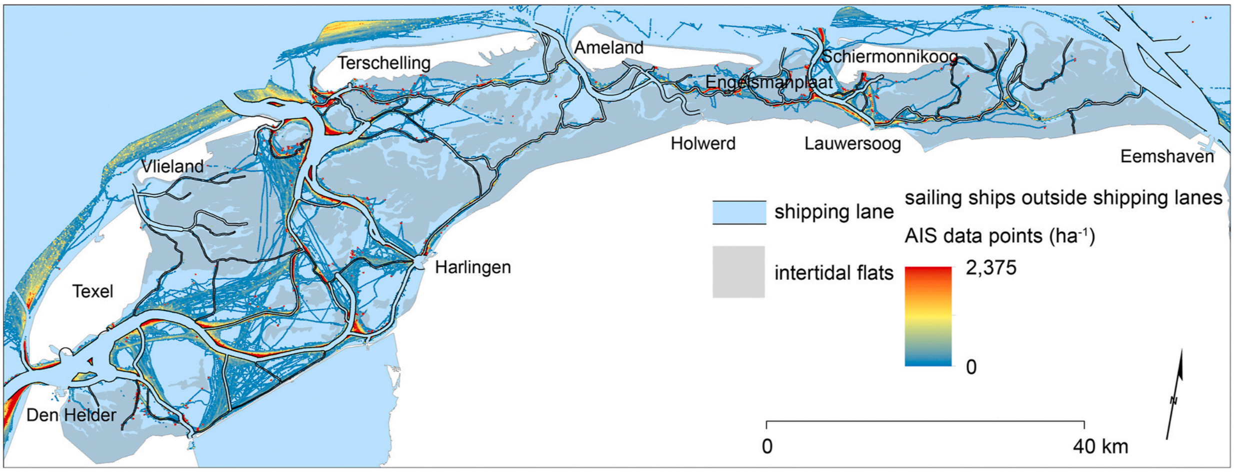

Fig. 5. Point density of sailing ships outside shipping lanes during the 2018 recreational season.

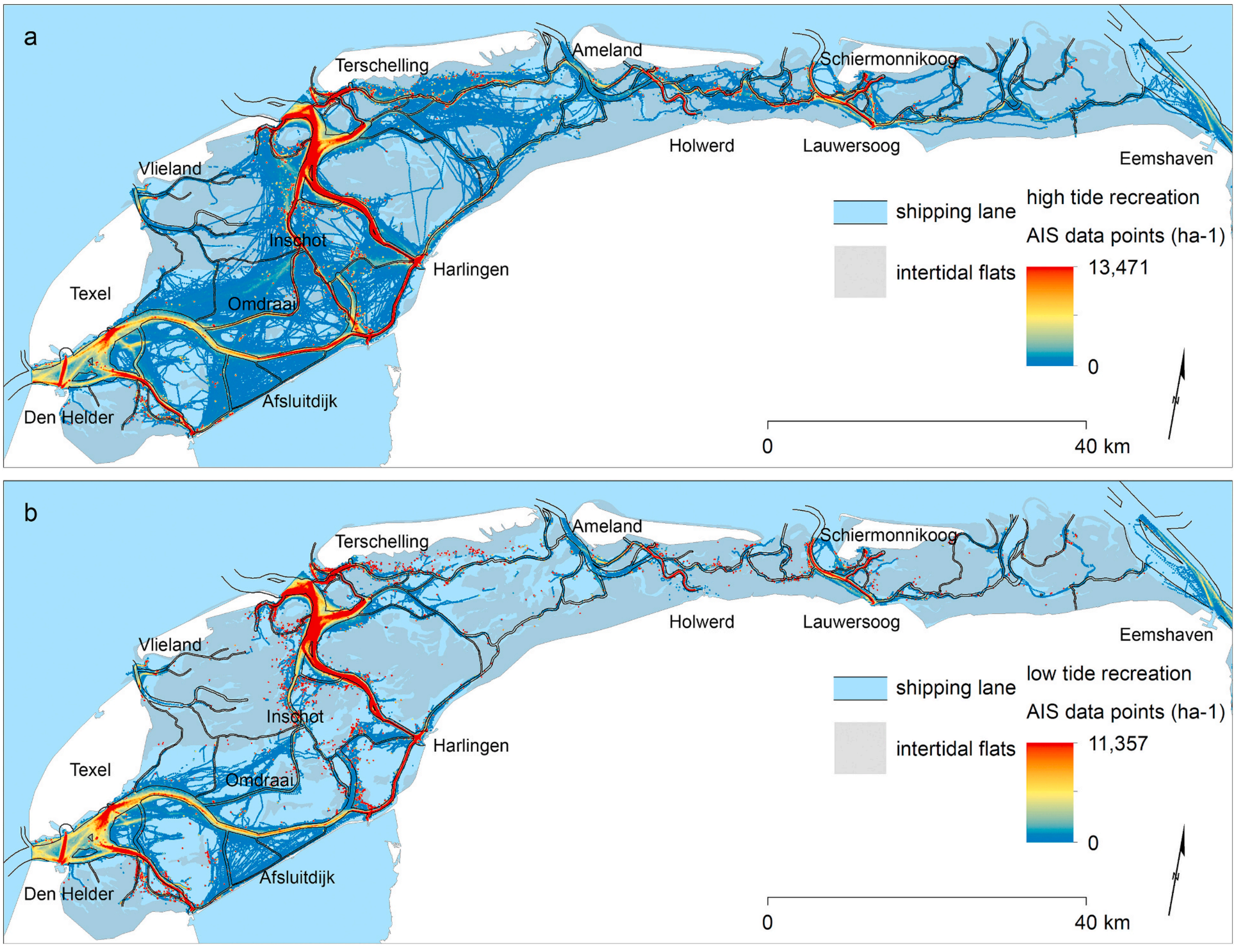

Fig. 6. Spatial patterns of recreation ships (excl. ferries) during (a) high tide and (b) low tide for the 2018 recreational season.

marine natural area. Our analysis delivered valuable visitor flow information specifically for the Wadden Sea area. We expect that such analyses can be adopted in other sensitive coastal waters as well, since AIS data are commercially available worldwide by network services such as ORBCOMM (e.g. Oozeki et al., 2017) or MarineTraffic (e.g. Deter et al., 2017). In some areas, AIS data can be obtained via regional coast guards (e.g., in Canada, see Erbe et al., 2014), maritime authorities (e.g., in Denmark, see Hermannsen et al., 2017) similar to the data-acquisition for the present study.

5.2. *Caveats of the AIS approach*

Overall, the use of AIS data appears to be a promising way to assess full season recreational patterns for a large area. Acquiring AIS is relatively easy since the data is readily available, and our standardised empirical approach can be transferred to other study areas. There are,

Table 3
General statistics of ships exceeding speed limits during the 2018 recreational season.

type	passenger ship		pleasure craft	sailing ship	total
	ferry	other			
AIS data points (count)	596,182	3,611,268	1,855,231	2,664,195	8,726,876
AIS data points > 20 kph (count)	243,301	184,026	106,903	41,635	575,865
AIS data points > 20 kph where allowed (count)	229,490	138,850	79,042	34,435	481,817
AIS data points > 20 kph where not allowed (count)	13,811	45,176	27,861	7,200	94,048
AIS data points > 20 kph (%)	40.8%	5.1%	5.7%	1.6%	6.5%
AIS data points > 20 kph where not allowed (%)	2.3%	1.3%	1.5%	0.3%	1.1%

however, some quality issues. Firstly, we have found that pre-processing of the AIS data is vital. Not only was it necessary to filter out terrestrial and in-port data points, but we have also found that location, draught and speed data are sometimes erroneous or non-existent, similar to Deter et al. (2017) for a Mediterranean coastline and Meijles et al. (2014) for a terrestrial natural area in The Netherlands. Therefore, we calculated speeds based on subsequent locations and we use the combination of tide and bathymetry to reconstruct water depth for each AIS data point. Because of the dynamic geomorphological processes in the tidal sea, with very active erosion and sedimentation processes locally, we found that some of the supporting spatial datasets outdated rather quickly. For our study, this was a problem, since the tidal sea is rather shallow. Particularly the bathymetry and the location of shipping lanes was susceptible to errors. Although it would be better to update the supporting spatial datasets on a more regular basis, it is unrealistic to do this more often than annually due to high costs. Manual interpretation of the most active gullies is therefore still necessary.

An important aspect of the analysis is the representativity. Although the AIS database might in an environmental management context be considered as big data, with nearly nine million records for a single season, some visitor groups are better represented than others (Hermannsen et al., 2019; Wawrzyniak & Stateczny, 2018). Passenger ships are obliged to actively use AIS so we can reasonably assume that most if not all of these ships are in the database. Although sailing ships and pleasure craft seem to be well represented with over four million datapoints, they should be considered as a sample since AIS use is voluntary. Not all skippers have their AIS equipment switched on, or do not have AIS on board (Cope et al., 2020; Hermannsen et al., 2019; Heslinga et al., 2019). To what extent this depends on different motivation groups is not known, but local experts have the impression that boating visitors particularly valuing the nature and quietness of the Wadden Sea are somewhat underrepresented in the AIS database (Vroom, 2017, pers. comm.). At the same time, other recreation activities (sea kayaking, tidal flat walking) are not being tracked since they do not carry AIS equipment. It may be useful to carry out a survey or census based on aerial photos to analyse the spatiotemporal behaviour of these activities. A recently developed recognition and identification video monitoring system by Wawrzyniak and Stateczny (2018) may be very useful in detecting such activities, although application may be possible for relatively small areas only. Using radar (Heslinga et al., 2019; Ilcev, 2019), recently developed micro-satellites (Lapierre et al., 2010) or combining such method with AIS data with other vessel tracking systems (Cope et al., 2020), may provide useful to fully assess and manage recreational traffic in coastal waters.

5.3. Spatiotemporal patterns in a tidal sea environment

For the Wadden Sea specifically, our findings confirmed quantitatively that the majority of the traffic takes place in the natural channels and shipping lanes. Most of the ships sailing outside the lanes still stay close to the channels. This might be due to avoiding the heavier traffic in the lanes themselves, but could also indicate some errors in either the local bathymetry, the location of shipping buoys or the shipping lane spatial database, since the Wadden Sea can be highly dynamic in places. In several MPAs at high tide the number of AIS tracks over the submerged tidal flats is relatively high. Although the intensity is still very much lower than in the main channels, due to our approach this intensity can now be monitored consistently.

Our analysis has also shown that based on AIS-data, tidal flat mooring can be mapped. This is important, because this is a highly valued recreational activity in the study area and may disturb feeding birds and resting seals but is otherwise difficult to monitor. We identified the most popular tidal flat mooring places and, at the same time, flats where mooring activity is limited. We found a relatively high rate of mooring activity in some Marine Protected Areas. This is important, since all major resting places of seals (including pupping areas) and breeding areas of birds are protected as MPA in the Dutch Wadden Sea. AIS data therefore is suitable to identify potentially problematic

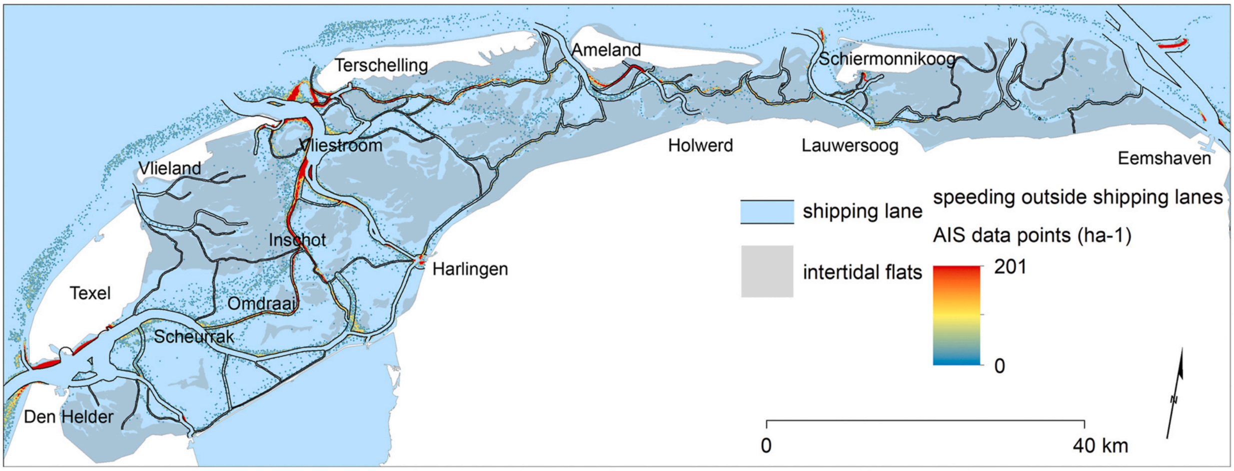

Fig. 7. Point density map of recreational craft (excl. ferries) exceeding the speed limit during the 2018 recreational season.

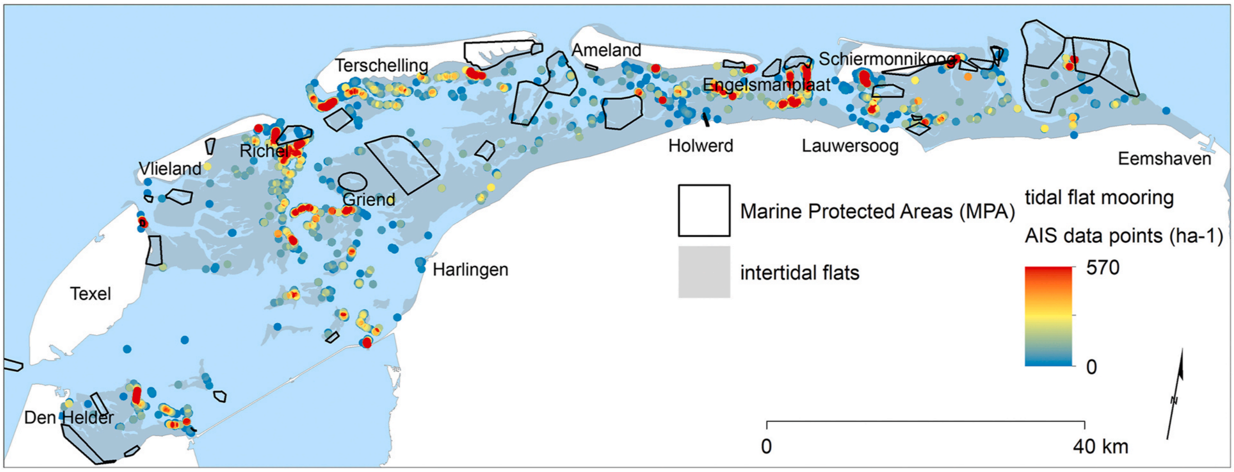

Fig. 8. Favourite tidal flat mooring locations shown by point density values.

Table 4
Tidal flat mooring per ship type for the 2018 recreational season.

type	passenger	pleasure craft	sailing ship	total
AIS data points				
total count	4,207,450	1,855,231	2,664,195	8,726,876
Tidal flat mooring (count)	140,061	76,398	48,134	264,593
Tidal flat mooring outside shipping lane (count)	128,480	60,190	41,058	229,728
Tidal flat mooring in MPA during restricted period (count)	6,638	10	330	6,678
Tidal flat mooring (%)	3.30%	4.10%	1.80%	3.00%
Tidal flat mooring in MPA during restricted period (%)	0.02%	0.00%	0.01%	0.08%

locations, which could inform park rangers about where to patrol more regularly.

Our monitoring results also suggest that sailing above the speed limit is not predominant behaviour: speeding behaviour is limited to 1%–2% of total AIS data-points in the area studied. In most cases, speeding appears close to shipping lanes. However, the effect of speeding on (local) birds and seals and other recreationists might be more severe than the data suggests.

In this paper, we focused on designing the methodology to map out spatiotemporal recreational boating. However, more research is needed to assess to what extent tourism negatively impacts the behaviour and population dynamics of birds and seals (Madsen, 2007; Van Roomen et al., 2012; Ashley et al., 2020.), including the proximity and speeding of recreational boats. To establish this, combining AIS data with spatially explicit ecological indicators and field observations offers a promising way forward. Van der Kolk et al. (2020) have already shown the value of such analyses by combining aircraft and shorebird data. For the Wadden Sea area, ecological geographic datasets such as bird feeding and resting hotspots and seal resting places would be the most logical next step.

5.4. Integrating AIS in an ecological monitoring system

Within the scope of this paper we could not address all management related questions that surround the monitoring of visitor flows in ecologically sensitive areas (e.g. Hadwen et al., 2007; Lyon et al., 2011;

Table 5
Logged recreational traffic per MPA for the recreational season in 2018.

	Restricted period	Activity			Ship type			
	(2018)	tidal flat mooring		sailing	passenger	pleasure	sailing	total
MPA			km^{-2}		ship	craft	ship	
Boswad Schild Lauwerswal	15/5-1/9	3,948	103	10,674	14,622	0	0	14,622
De Cocksdorp	Permanent	1,045	3477	178	1,223	0	0	1,223
Rottumeroog	Permanent	836	49	1,054	1,610	0	280	1,890
Blauwe Balg noord[a]	1/4-1/9	461	30	3,493	412	98	3,444	3,954
Blauwe Balg zuid	15/5-1/9	162	10	466	587	20	21	628
Zuiderduintjes	15/5-1/9	160	9	255	306	88	21	415
Het Rif[c]	Dynamic	33	9	134	44	7	116	167
Holwerd veerdam[b]	1/4–15/8	19	59	2	21	0	0	21
Richel	Permanent	12	2	1,403	977	198	240	1,415
Total[d]		**6,678**	**23**	**25,807**	**26,140**	**1,404**	**4,941**	**32,485**

[a] Laying idle, anchoring and drifting is prohibited. Passage only allowed from 3 h before to 2 h after high tide.

[b] Not indicated on (paper) nautical maps in 2018.

[c] Prohibited in the period from 3 h before to 2 h after high tide.

[d] Only the MPAs shown with logged AIS data points. The full table can be found in the Supplementary Material.

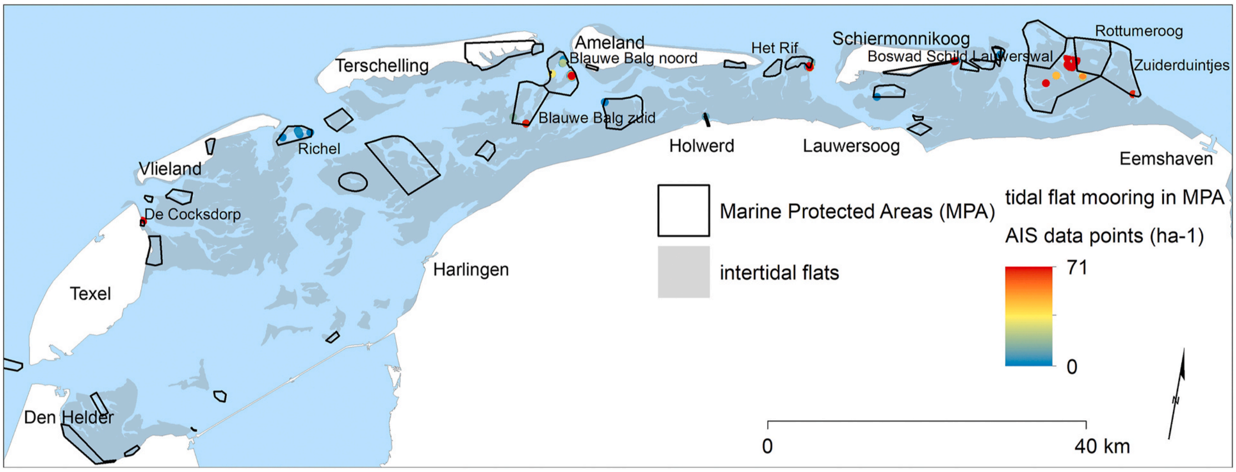

Fig. 9. Point density of recreational ships in MPAs during low tide in the 2018 recreational season. Areas with highest intensities are labelled.

Schlacher et al., 2013; Wimpey & Marion, 2011). We expect our methodology of assessing recreational boating patterns to be particularly useful in relation to environmental pressures. Firstly, the AIS data and resulting recreational pressure maps can be used to identify possible areas where recreation could conflict with (sensitive) natural areas. For example, Deter et al. (2017) have shown, that by combining AIS with seabed maps, damage to seagrass beds in ecological sensitive coastal waters could be identified. Also, it has been shown that anthropogenic underwater noise can be harmful to marine mammals (such as seals) and may affect their behaviour and communication (Erbe, 2012; Merchant et al., 2014). Although in deep sea, AIS data maps can be constructed showing the ambient noise (Erbe et al., 2014), until recently, lack of AIS data prevented this kind of analyses in shallow waters (Magnier & Gervaise, 2020). This is important, since shallow waters have the tendency to dampen low frequency noise from larger ships, but increase mid-to-high frequency noise, usually from smaller recreational ships (Hermannsen et al., 2019).

For the Wadden Sea, using spatially explicit bird data on high tide roosts, rich feeding grounds, locations of moulting ducks and breeding colonies during the breeding season combined with spatiotemporal AIS analysis could provide detailed insights in possible pressure locations. This holds also true for seal haul out and suckling young sites. Although our analysis will not replace field-based observations, it does provide a method to analyse such pressures for a large area for a full season, which was not possible previously with field observations only. Therefore, we recommend further developing the methodology by combining spatiotemporal recreational patterns with ecological indicator data and to create synergy with field monitoring.

Secondly, the smallest recreational crafts in the area, such as small speed boats, water taxis, sea kayaks, kite surfers and tidal flat walkers are currently not recorded in the data. Although their numbers are substantially lower than sailing and pleasure craft, they are part of the typical recreational activities in shallow coastal waters, and may also have impact on natural values. The current AIS analysis method could therefore be extended to also include radar data, since these data capture all movements, including smaller craft that is currently not using AIS (Cope et al., 2020; Wawrzyniak & Stateczny, 2018). However, radar data would require extensive filtering to produce a ‘signal’ of recreational activity. In addition, other mobile data, such as STRAVA, other voluntary use of GPS data or other crowd mobile data sources may be good alternatives. It is essential, however, to also combine this with field observations to validate AIS and radar signals.

Thirdly, our method allows for monitoring over longer time periods. To identify trends in recreational behaviour, or the effectiveness of possible policy measures, the method can be further standardised as a monitoring methodology for the coming years. At the same time, as AIS data have been stored for several years now, monitoring can also take place retrospectively. For management purposes, trends or stepwise changes can be better identified if the methodology is carried out in a long-term standardised way.

We can therefore conclude that AIS technology can provide a useful tool for studying recreational pressures for longer periods and for large areas, and can be further developed to also assess more concrete relationships with natural values, in which both the experience of visitors as well as the ecological quality are considered.

Author statement

Erik Meijles: conceptualization, methodology, programming, formal analysis, data curation, writing (original draft and review & editing), visualization, funding acquisition; **Michiel Daams:** conceptualization, programming, writing (original draft and review & editing); **Bruno Ens:** conceptualization, methodology, writing (original draft and review & editing), funding acquisition; **Jasper Heslinga:** methodology, writing (original draft and review & editing); funding acquisition; **Frans Sijtsma:** conceptualization, writing (original draft and review & editing), visualization, funding acquisition.

Funding

Financial support for this study was obtained from the Centre of Expertise Tourism, Leisure and Hospitality (CELTH) and Actieplan Vaarrecreatie Waddenzee and is part of the programme ‘Programma naar een Rijke Waddenzee’.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgements

We would like to thank Marjan Vroom, Bertus van der Tuuk, Els van der Zee and Eelke van der Veen for the very fruitful MOCO cooperation and for critical comments on earlier versions of the manuscript. We are thankful to Nautin for providing us with recent buoy data. The contribution of the InterTides model by Cees Rappoldt is very much appreciated. We would also like to thank the anonymous reviewers for their constructive feedback.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2021.102441.

References

Ashley, E. A., Olson, J. K., Adler, T. E., Raverty, S., Anderson, E. M., Jeffries, S., & Gaydos, J. K. (2020). Causes of mortality in a harbor seal (Phoca vitulina) population at equilibrium. *Frontiers in Marine Science, 7*(319), 1–11. https://doi.org/10.3389/fmars.2020.00319

Balaguer, P., Diedrich, A., Sardá, R., Fuster, M., Cañellas, B., & Tintoré, J. (2011). Spatial analysis of recreational boating as a first key step for marine spatial planning in Mallorca (Balearic Islands, Spain). *Ocean & Coastal Management, 54*, 241–249. https://doi.org/10.1016/j.ocecoaman.2010.12.002

Beeco, J. A., Hallo, J. C., English, W. R., & Giumetti, G. W. (2013). The importance of spatial nested data in understanding the relationship between visitor use and landscape impacts. *Applied Geography, 45*, 147–157. https://doi.org/10.1016/j.apgeog.2013.09.001

Beeco, J. A., Huang, W. J., Hallo, J. C., Norman, W. C., McGehee, N. G., McGee, J., & Goetcheus, C. (2013). GPS tracking of travel routes of wanderers and planners. *Tourism Geographies, 15*(3), 551–573. https://doi.org/10.1080/14616688.2012.726267

Beunen, R., Regnerus, H. D., & Jaarsma, C. F. (2008). Gateways as a means of visitor management in national parks and protected areas. *Tourism Management, 29*(1), 138–145. https://doi.org/10.1016/j.tourman.2007.03.017

Buckley, R. (2012). Sustainable tourism: Research and reality. *Annals of Tourism Research, 39*(2), 528–546. https://doi.org/10.1016/j.annals.2012.02.003

Chantre-Astaiza, A., Fuentes-Moraleda, L., Muñoz-Mazón, A., & Ramirez-Gonzalez, G. (2019). Science mapping of tourist mobility 1980–2019. Technological advancements in the collection of the data for tourist traceability. *Sustainability, 11*(17), 1–32. https://doi.org/10.3390/su11174738

Cope, S., Hines, E., Bland, R., Davis, J. D., Tougher, B., & Zetterlind, V. (2020). Application of a new shore-based vessel traffic monitoring system within san francisco bay. *Frontiers in Marine Science, 7*(86), 1–13. https://doi.org/10.3389/fmars.2020.00086

Croxall, J. P., Butchart, S. H. M., Lascelles, B., Stattersfield, A. J., Sullivan, B., Symes, A., & Taylor, P. (2012). Seabird conservation status, threats and priority actions: A global assessment. *Bird Conservation International, 22*(1), 1–34. https://doi.org/10.1017/S0959270912000020

Davenport, J., & Davenport, J. L. (2006). The impact of tourism and personal leisure transport on coastal environments: A review. *Estuarine. Coastal and Shelf Science, 67*(1–2), 280–292. https://doi.org/10.1016/j.ecss.2005.11.026

Deter, J., Lozupone, X., Inacio, A., Boissery, P., & Holon, F. (2017). Boat anchoring pressure on coastal seabed: Quantification and bias estimation using AIS data. *Marine Pollution Bulletin, 123*(1–2), 175–181. https://doi.org/10.1016/j.marpolbul.2017.08.065

Dutch Government. (2016). https://www.rijksoverheid.nl/onderwerpen/natuur-en-biodiversiteit/nieuws/2016/10/31/gekozen-tot-mooiste-natuurgebieden-van-nederland. (Accessed 2 November 2019).

Dye, A. S., & Shaw, S. L. (2007). A GIS-based spatial decision support system for tourists of Great Smoky Mountains National Park. *Journal of Retailing and Consumer Services, 14*(4), 269–278. https://doi.org/10.1016/j.jretconser.2006.07.005

Elias, E. (2017). *Kustgenese 2.0; available measurements and bathymetric data at Ameland inlet, The Netherlands. Deltares*. The Netherlands https://www.helpdeskwater.nl/publish/pages/156530/1220339-007-zks-0001-r-kustgenese_2_0_available_measurements_and_bathymetric_data_at_ameland_inlet.pdf. (Accessed January 2021).

Elias, E., & Wang, Z. B. (2013). *Abiotische gegevens voor monitoring effect bodemdaling. Rapport*. Delft, The Netherlands.

Erbe, C. (2012). The effects of underwater noise on marine mammals. In A. N. Popper, & A. D. Hawkins (Eds.), *The effects of noise on aquatic life advances in experimental medicine and biology 730* (pp. 17–22). New York: Springer Verlag.

Erbe, C., Williams, R., Sandilands, D., & Ashe, E. (2014). Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific region. *PLoS One, 9*(11), Article e89820. https://doi.org/10.1371/journal.pone.0089820

Freuler, B., & Hunziker, M. (2007). Recreation activities in protected areas: Bridging the gap between the attitudes and behaviour of snowshoe walkers. *Forest Snow and Landscape Research, 81*(1/2), 191–206. https://www.dora.lib4ri.ch/wsl/islandora/object/wsl:15346.

Geneletti, D., & Van Duren, I. (2008). Protected area zoning for conservation and use: A combination of spatial multicriteria and multiobjective evaluation. *Landscape and Urban Planning, 85*(2), 97–110. https://doi.org/10.1016/j.landurbplan.2007.10.004

Hadwen, W. L., Hill, W., & Pickering, C. M. (2007). Icons under threat: Why monitoring visitors and their ecological impacts in protected areas matters. *Ecological Management and Restoration, 8*(3), 177–181. https://doi.org/10.1111/j.1442-8903.2007.00364.x

Hallo, J. C., Beeco, A., Goetcheus, C., McGee, J., McGehee, N. G., & Norman, W. C. (2012). GPS as a method for assessing spatial and temporal use distributions of nature-based tourists. *Journal of Travel Research, 51*(5), 591–606. https://doi.org/10.1177/0047287511431325

Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., & Madsen, P. T. (2019). Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. *Scientific Reports, 9*, 1–10. https://doi.org/10.1038/s41598-019-51222-9, 15477.

Heslinga, J. H., Groote, P. D., & Vanclay, F. (2018). Understanding the historical institutional context by using content analysis of local policy and planning documents. *Tourism Management, 66*, 180–190. https://doi.org/10.1016/j.tourman.2017.12.004

Heslinga, J. H., Sijtsma, F. S., & Van der Veen, E. (2019). *Gedrag vaarrecreanten op de Waddenzee – seizoen 2018*. Leeuwarden: European Tourism Futures Institute (ETFI).

Ilcev, D. S. (2019). Introduction to coastal HF maritime surveillance radars. *Polish Maritime Research, 3*(26), 153–162. https://doi.org/10.2478/pomr-2019-0056

IMO. (2019). http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx. (Accessed 30 October 2019).

Kaiser, M. J., & Narra, S. (2014). Application of AIS data in service vessel activity description in the Gulf of Mexico. *Maritime Economics & Logistics, 16*, 436–466. https://doi.org/10.1057/mel.2014.25

Kleefstra, R., Smit, C., Kraan, C., Aarts, G., van Dijk, J., & de Jong, M. (2011). Het toegenomen belang van de Nederlandse Waddenzee voor ruiende Bergeenden. *Limosa, 84*, 145–154.

Kloepper, S., Baptist, M. J., Bostelmann, A., Busch, J. A., Buschbaum, C., Gutow, L., Janssen, G., Jensen, K., Jørgensen, H. P., De Jong, F., Lüerßen, G., Schwarzer, K., Strempel, R., & Thieltges, D. (2017). *Wadden Sea quality status report 2017*. Common Wadden Sea Secretariat, Wilhelmshaven, Germany https://qsr.waddensea-worldheritage.org/. (Accessed 30 April 2020).

Korpilo, S., Virtanen, T., & Lehvävirta, S. (2017). Smartphone GPS tracking—inexpensive and efficient data collection on recreational movement. *Landscape and Urban Planning, 157*, 608–617. https://doi.org/10.1016/j.landurbplan.2016.08.005

Lapierre, F., Borghgraef, A., & Vandewal, M. (2010). Statistical real-time model for performance prediction of ship detection from microsatellite electro-optical imagers. *EURASIP Journal on Applied Signal Processing, 475948*, 1–15. https://doi.org/10.1155/2010/475948

Lera, I., Pérez, T., Guerrero, C., Eguíluz, V. M., & Juiz, C. (2017). Analysing human mobility patterns of hiking activities through complex network theory. *PloS One, 12*(5), 1–19. https://doi.org/10.1371/journal.pone.0177712

Libosada, C. M. (2009). Business or leisure? Economic development and resource protection-concepts and practices in sustainable ecotourism. *Ocean & Coastal Management, 52*(7), 390–394. https://doi.org/10.1016/j.ocecoaman.2009.04.004

Liley, D., & Sutherland, W. J. (2007). Predicting the population consequences of human disturbance for ringed plovers Charadrius hiaticula: A game theory approach. *Ibis International Journal of Avian Science, 149*(1), 82–94. https://doi.org/10.1111/j.1474-919X.2007.00664.x

Long, J., & Robertson, C. (2018). Comparing spatial patterns. *Geography Compass, 12*, 1–18. https://doi.org/10.1111/gec3.12356

Lyon, K., Cottrell, S. P., Siikamaki, P., & Van Marwijk, R. B. M. (2011). Biodiversity hotspots and visitor flows in oulanka national park, Finland. *Scandinavian Journal of Hospitality and Tourism, 11*(1), 100–111. https://doi.org/10.1080/15022250.2011.629909

Madsen, J. (2007). *Possible effects and impacts of recreational activities on bird populations in the Wadden Sea - can disturbance explain the negative trends? Seriously declining trends in migratory waterbirds: Causes-Concerns-Consequences*. In B. Reineking, & P. Südbeck (Eds.) (pp. 65–68). Wilhelmshaven: Common Wadden Sea Secretariat.

Magnier, C., & Gervaise, C. (2020). Acoustic and photographic monitoring of coastal maritime traffic: Influence on the soundscape. *Journal of the Acoustical Society of America, 147*, 3749–3757. https://doi.org/10.1121/10.0001321

McCool, S. F., & Spenceley, A. (2014). Tourism and protected areas: A growing nexus of challenge and opportunity. *Koedoe, 56*(2), 1–2.

Meijles, E. W., De Bakker, M., Groote, P., & Barske, R. (2014). Analysing hiker movement patterns using GPS data: Implications for park management. *Computers, Environment and Urban Systems, 47*, 44–57. https://doi.org/10.1016/j.compenvurbsys.2013.07.005

Merchant, N. D., Pirotta, E., Barton, T. R., & Thompson, P. M. (2014). Monitoring ship noise to assess the impact of coastal developments on marine mammals. *Marine Pollution Bulletin, 78*(1–2), 85–95. https://doi.org/10.1016/j.marpolbul.2013.10.058

Nautin. (2020). https://www.nautin.nl/wb/pages/home.php. (Accessed 19 January 2020).

Newsome, D., Moore, S. A., & Dowling, R. K. (2013). *Natural area tourism: Ecology, impacts and management*. Bristol: Channel View Publications.

O'Connor, A., Zerger, A., & Itami, B. (2005). Geo-temporal tracking and analysis of tourist movement. *Mathematics and Computers in Simulation, 69*(1/2), 135–150. https://doi.org/10.1016/j.matcom.2005.02.036

Oozeki, Y., Inagake, D., Saito, T., Okazaki, M., Fusejima, I., Hotai, M., Watanabe, T., Sugisaki, H., & Miyahara, M. (2018). Reliable estimation of IUU fishing catch amounts in the northwestern Pacific adjacent to the Japanese EEZ: Potential for usage of satellite remote sensing images. *Marine Policy, 88*, 64–74. https://doi.org/10.1016/j.marpol.2017.11.009

Orellana, D., Bregt, A. K., Ligtenberg, A., & Wachowicz, M. (2012). Exploring visitor movement patterns in natural recreational areas. *Tourism Management, 33*(3), 672–682. https://doi.org/10.1016/j.tourman.2011.07.010

Parrott, L., Chion, C., Martins, C. C. A., Lamontagne, P., Turgeon, S., Landry, J. A., Zhens, B., Marceau, D. J., Michaud, R., Cantin, G., Ménard, N., & Dionne, S. (2011). A decision support system to assist the sustainable management of navigation activities in the St. Lawrence River Estuary, Canada. *Environmental Modelling & Software, 26*(12), 1403–1418. https://doi.org/10.1016/j.envsoft.2011.08.009

Pouwels, R., Van Eupen, M., Walvoort, D. J. J., & Jochem, R. (2020). Using GPS tracking to understand the impact of management interventions on visitor densities and bird populations. *Applied Geography, 116*, Article 102154. https://doi.org/10.1016/j.apgeog.2020.102154

Rappoldt, C., Roosenschoon, O. R., & Van Kraalingen, D. W. (2014). *InterTides: Maps of the intertidal by interpolation of tidal gauge data. Ecocurves report. 19*.

Rijkswaterstaat. (2013). https://www.rijkswaterstaat.nl/water/waterdata-en-waterberichtgeving/metingen/waternormalen/index.aspx Last. (Accessed 13 November 2019).

Schlacher, T. A., Nielsen, T., & Weston, M. A. (2013). Human recreation alters behaviour profiles of non-breeding birds on open-coast sandy shores. *Estuarine, Coastal and Shelf Science, 118*, 31–42. https://doi.org/10.1016/j.ecss.2012.12.016

Shoval, N., & Isaacson, M. (2007). Tracking tourists in the digital age. *Annals of Tourism Research, 34*(1), 141–159. https://doi.org/10.1016/j.annals.2006.07.007

Sijtsma, F. J., Daams, M. N., Farjon, H., & Buijs, A. E. (2012). Deep feelings around a shallow coast: A spatial analysis of tourism jobs and the attractivity of nature in the Dutch wadden area. *Ocean & Coastal Management, 68*, 138–148. https://doi.org/10.1016/j.ocecoaman.2012.05.018

Sijtsma, F. J., Mehnen, N., Angelstam, P., & Muñoz-Rojas, J. (2019). Multi-scale mapping of cultural ecosystem services in a socio-ecological landscape: A case study of the international Wadden Sea region. *Landscape Ecology, 34*(7), 1751–1768. https://doi.org/10.1007/s10980-019-00841-8

Silveira, P., Teixeira, A., & Soares, C. (2013). Use of AIS Data to characterise marine traffic patterns and ship collision risk off the coast of Portugal. *Journal of Navigation, 66*(6), 879–898. https://doi.org/10.1017/S0373463313000519

Smallwood, C. B., Beckley, L. E., & Moore, S. A. (2012). An analysis of visitor movement patterns using travel networks in a large marine park, north-western Australia. *Tourism Management, 33*(3), 517–528. https://doi.org/10.1016/j.tourman.2011.06.001

Stamberger, L., Van Riper, C. J., Keller, R., Brownlee, M., & Rose, J. (2018). A GPS tracking study of recreationists in an Alaskan protected area. *Applied Geography, 93*, 92–102. https://doi.org/10.1016/j.apgeog.2018.02.011

Steven, R., & Castley, J. G. (2013). Tourism as a threat to critically endangered and endangered birds: Global patterns and trends in conservation hotspots. *Biodiversity & Conservation, 22*, 1063–1082. https://doi.org/10.1007/s10531-013-0470-z

Sykes, J., Hendrikx, J., Johnson, J., & Birkeland, K. W. (2020). Combining GPS tracking and survey data to better understand travel behavior of out-of-bounds skiers. *Applied Geography, 122*, Article 102261. https://doi.org/10.1016/j.apgeog.2020.102261

Taczanowska, K., González, L. M., Garcia-Massó, X., Muhar, A., Brandenburg, C., & Toca-Herrera, J. L. (2014). Evaluating the structure and use of hiking trails in recreational areas using a mixed GPS tracking and graph theory approach. *Applied Geography, 55*, 184–192. https://doi.org/10.1016/j.apgeog.2014.09.011

Taczanowska, K., Muhar, A., & Brandenburg, C. (2008). Potential and limitations of GPS tracking for monitoring spatial and temporal aspects of visitor behaviour in recreational areas. In A. Raschi, & S. Trampetti (Eds.), *Management for protection and sustainable development* (pp. 451–455). Montecatini, Italy: Conciglio Nationale della Ricerche.

Tjaden, J., Westra, H., & Venema, H. (2018). *Programmaplan 2019-2022* (p. 72p). The Hague, The Netherlands: Programma naar een Rijke Waddenzee.

UNESCO (2009). http://whc.unesco.org/en/decisions/1946. (Last accessed 40 04 2020).

Van Marwijk, R. B. M. (2009). *These routes are made for walking: Understanding the transactions between nature.* recreational behaviour and environmental meanings in Dwingelderveld National Park, the Netherlands. PhD thesis (p. 260p). Wageningen University.

Van Roomen, R., Laursen, K., Van Turnhout, C., Van Winden, E., Blew, J., Eskildsen, K., Günther, K., Hälterlein, B., Kleefstra, R., Potel, P., Schrader, S., Luerssen, G., & Ens, B. J. (2012). Signals from the Wadden sea: Population declines dominate among waterbirds depending on intertidal mudflats. *Ocean & Coastal Management, 68*, 79–88. https://doi.org/10.1016/j.ocecoaman.2012.04.004

Van den Bemt, V., Doornbos, J., Meijering, L. B., Plegt, M., & Theunissen, N. (2018). Teaching ethics when working with geocoded data: A novel experiential learning approach. *Journal of Geography in Higher Education, 42*(2), 293–310. https://doi.org/10.1080/03098265.2018.1436534

Van der Kolk, H. J., Allen, A. M., Ens, B. J., Oosterbeek, K., Jongejans, E., & Van de Pol, M. (2020). Spatiotemporal variation in disturbance impacts derived from simultaneous tracking of aircraft and shorebirds. *Journal of Applied Ecology, 57*, 2406–2418. https://doi.org/10.1111/1365-2664.13742

WaLTER. (2020). https://www.walterwaddenmonitor.org/en/. (Accessed 19 February 2020).

Wawrzyniak, N., & Stateczny, A. (2018). Automatic watercraft recognition and identification on water areas covered by video monitoring as extension for sea and river traffic supervision systems. *Polish Maritime Research, 25*, 5–13. https://doi.org/10.2478/pomr-2018-0016

Wesley, A., & Pforr, C. (2010). The governance of coastal tourism: Unravelling the layers of complexity at smiths beach, western Australia. *Journal of Sustainable Tourism, 18*(6), 773–792. https://doi.org/10.1080/09669581003721273

Wimpey, J., & Marion, J. L. (2011). A spatial exploration of informal trail networks within Great Falls Park, VA. *Journal of Environmental Management, 92*, 1012–1022. https://doi.org/10.1016/j.jenvman.2010.11.015

Wolf, I. D., Hagenloh, G., & Croft, D. B. (2012). Visitor monitoring along roads and hiking trails: How to determine usage levels in tourist sites. *Tourism Management, 33*(1), 16–28. https://doi.org/10.1016/j.tourman.2011.01.019

Xiao-Ting, H., & Bi-Hu, W. (2012). Intra-attraction tourist spatial-temporal behaviour patterns. *Tourism Geographies, 14*(4), 625–645. https://doi.org/10.1080/14616688.2012.647322