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Editorial

Editorial

Welcome to the latest edition of the International Hydrographic Review. I am honored to take on the responsibility as Editor of our community's oldest scientific publication. All of us owe Alberto Costa Neves our appreciation for his efforts as Acting Editor of IHR – he stepped in and took on a difficult position while still finding time for his Assistant Director duties. I especially want to thank him for his patience during our extended, and remote, turnover.

When I agreed to take on the Editor's role last year, I certainly wasn't expecting the situation we find ourselves in right now. Like many of you, I have been adapting my routine to comply with social distancing guidelines, stay at home orders, and a host of other constraints. I have become a pseudo-expert on many different video conferencing platforms, home office design, and methods for remote collaboration. The impact of this pandemic on the hydrographic community has been substantial, but as hydrographers, we adapt, innovate, and do whatever it takes to get the job done. In speaking with many of our colleagues around the world, I have been impressed by their positive response to adversity, creative solutions, and laser focus on providing information to users. In the long term, I believe we will all benefit from the new technology, techniques and processes that are being adopted now, especially in remote operations and data management.

The IHR has served as the IHO's journal since 1923 and has adapted over the years in format, content, and dissemination methods. It is my goal to continue the evolution of the IHR to best serve the needs of the IHO and the hydrographic community. For example, you can see the IHR appearance has changed to follow the new IHO branding scheme. Not all changes will be cosmetic; it is most important that the IHR maintain the highest standard for published papers. The Editorial Board and I will work aggressively to increase the quality and quantity of articles and notes, however, we need your help to achieve success. Over the years, many papers that could have been published in the IHR have been placed in other scientific and professional journals due to a perception that the IHR was not impactful or had a low readership. We plan to change that perception and make IHR the journal of choice for hydrographic content. So, I encourage all of you to submit your articles and notes to the IHR for consideration.

This edition is comprised of 3 articles and 2 notes addressing a variety of relevant topics. The first article discusses the application of two safety of navigation risk assessment techniques, one from the International Association of Aids to Marine Navigation and Lighthouse Authorities (IALA) and the other from Land Information New Zealand (LINZ), in Trinidadian waters of the Gulf of Paria. The second article discusses the use of optical satellite imagery of turbid waters to detect vortex structures. These vortices can be used to locate underwater hazards and determine local current properties. The third article takes a comprehensive look at the creation of a Baltic Sea Chart Datum. This effort, started in 2005, has resulted in a common chart datum across the member states of the Baltic Sea Hydrographic Commission (BSHC). The members of the BSHC are to be commended for their perseverance, diligence, and hard work to complete this monumental task.

Our first note continues the discussion from the last IHR edition of “hydrospatial” as a new word to better capture today’s digital hydrographic relationships. The author employed a unique method of interviewing leaders of hydrography at the 2020 Canadian Hydrographic Conference and capturing input from the audience. The second note captures the story of Tropical Cyclone IDAI’s impact on the hydrographic capability of Mozambique. As hydrographers, all of us have responded to natural and man-made disasters, however, this note provides insight into the short- and long-term effects these disasters can have on a hydrographic office.

The hydrographic community mourns the loss of Dr. Salem Masry, who passed away earlier this year. Dr. David Wells, a long-time friend of Dr. Masry, contributed a touching obituary.
I hope you enjoy this edition of IHR!

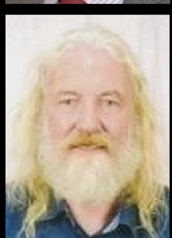
Brian Connon
Editor

Articles

BENEFITS OF ASSESSING RISK IN MARITIME NAVIGATION USING IALA AND LINZ METHODS

By D. Seepersad [1,2], O. Erikson [2], A. Greenland [3], K. Miller [1]

1 - Department of Geomatics Engineering, and Land Management, the University of the West Indies.
2 - International Association of Aids to Marine Navigation and Lighthouse Authorities (IALA).
3 - New Zealand Hydrographic Authority, Land Information New Zealand (LINZ).



Abstract

Introduction of the Automatic Identification System (AIS) for shipping has led to use of archived data in risk assessment for maritime navigation. The IWRAP software from the International Association of Aids to Navigation and Lighthouse Authorities (IALA) makes use of statistics derived from AIS data to determine likelihood of collision and grounding events in waterways where maritime traffic follows regular routes. Alternatively, the New Zealand Hydrographic Authority implemented a weighted overlay in a Geographic Information System (GIS) using AIS data together with further geographical information of a waterway to determine risk. These methods are tested in Trinidadian waters of the Gulf of Paria to identify benefits. It is concluded that each method offers a different contribution to the decision making process for improvement to the safety of navigation.

Résumé

L'introduction du système d'identification automatique (AIS) pour la navigation a conduit à l'utilisation de données archivées dans l'évaluation des risques pour la navigation maritime. Le logiciel IWRAP de l'Association internationale de signalisation maritime (AISM) utilise des statistiques dérivées des données AIS afin de déterminer les probabilités d'abordage et d'échouement sur les voies navigables où le trafic maritime suit des routes régulières. Par ailleurs, l'autorité hydrographique néo-zélandaise a mis en place une superposition pondérée dans un système d'information géographique (SIG) utilisant les données AIS ainsi que d'autres informations géographiques d'une voie navigable pour déterminer le risque. Ces méthodes sont testées dans les eaux trinidadiennes du golfe de Paria pour en déterminer les avantages. Il est conclu que chaque méthode apporte une contribution différente au processus de prise de décision pour l'amélioration de la sécurité de la navigation.

Articles

Resumen

La introducción del Sistema de Identificación Automática (SIA) para la navegación ha llevado a utilizar datos archivados en la evaluación de riesgos para la navegación marítima. El programa informático IWRAP de la Asociación Internacional de Ayudas a la Navegación Marítima y Autoridades de Faros (IALA) utiliza las estadísticas derivadas de los datos del SIA para determinar la probabilidad de que se produzcan colisiones y varadas en las vías navegables en las que el tráfico marítimo sigue las rutas habituales. Alternativamente, la Autoridad Hidrográfica de Nueva Zelanda implementó una superposición ponderada en un Sistema de Información Geográfica (SIG) utilizando datos del SIA junto con más información geográfica de una vía navegable para determinar el riesgo. Estos métodos se prueban en las aguas de Trinidad del Golfo de Paria para determinar los beneficios. Se llega a la conclusión de que cada método ofrece una contribución diferente al proceso de toma de decisiones para mejorar la seguridad de la navegación.

1. Introduction

Any means of transportation involves risk to human life, the environment and property; shipping is no exception. Catastrophic incidents involving ships are rare, but when they do occur the magnitude of the event is extreme. On assessment of long-term monitoring of particular species in response to the *Exxon Valdez* oil spill of 1989, Bodkin et al (2014) conclude their report by stating that effects of oil can persist for decades in some species. In 2012 the cruise liner *Costa Concordia* carrying 4252 passengers struck a rock on the sea floor and capsized resulting in 32 deaths. The BBC (2014) reports that the salvage operation took 2 years and cost 2 billion USD with the vessel eventually being scrapped. In both cases the root cause of the incident was attributed to human error. McCafferty and Baker (2006) explain how an investigation proceeds through considering causal factors that lead to the root cause. Such incidents can rarely be attributed to a single factor, it is typically a combination of a number of small factors combined that lead to such an incident, as in the case of the cruise ship *L'Austral*. Operating in the vicinity of Snares Island, south of New Zealand in 2017, during an excursion involving small launches, the weather deteriorated. In the process of launch recovery the vessel drifted into waters marked on the chart as an exclusion zone and struck an uncharted rock. In this instance, the weather conditions led to pre-occupation of the master with the recovery operation, who then failed to observe the vessel drift into an area of known hazards. It is not uncommon for mariners to navigate through poorly charted waters by local knowledge, but there is a chance that an unknown obstruction may lie beneath the sea surface in the vicinity. Causal factors relating to chart adequacy and environmental conditions are available from the geography of a region, there is then potential to undertake a risk assessment.

A number of approaches for assessing risk in the process of maritime navigation have been implemented at a national level (Ward and Gallagher, 2011; Chenier, Abado and Martin, 2018; and, Kiemola et al, 2009). Under the South-West Pacific Regional Hydrographic Programme, Land Information New Zealand (LINZ), the NZ Hydrographic Authority in conjunction with Marico Marine New Zealand Limited provided an approach that has been applied to territories in the South-West Pacific using a method presented by Riding and Rawson (2015) with a view to wider use. Also, the International Association of Aids to Marine Navigation and Lighthouse Authorities (IALA) have developed the IALA Waterway Risk Assessment Programme (IWRAP) as a software (Friis-Hansen, 2008), which is available at a cost and with training. IWRAP provides one component of the overall IALA risk assessment process. Both the LINZ and IALA approaches are intended to meet the International Maritime Organisation (IMO) Formal Safety Assessment (FSA) process to managing risk detailed by the IMO (2002). From this perspective, the LINZ and IALA approaches are assessed in the Gulf of Paria, an almost enclosed body of water between Trinidad and Venezuela where navigational risk has not been previously evaluated. Sheltered waters of the Gulf serve as the route to the primary ports of the industrial island of Trinidad in the Republic of Trinidad and Tobago. A significant petrochemical industry together with regular cargo, ferry services and cruise liners mean that maritime traffic in the sheltered waters of the Gulf is diverse and dense. There are no Vessel Traffic Services (VTS) or Traffic Separation Schemes (TSS), but pilotage is a requirement for larger vessels through the dredged channels into the major ports. Through application of the LINZ approach to risk assessment in navigation and use of IWRAP, research considers these techniques with respect to implementation, data requirements and results to demonstrate benefits and constraints of the assessment methods in decision support. Research was undertaken independently by staff from the University of the West Indies under the guidance of staff from LINZ and IALA, thereby providing a unique unbiased perspective that is corroborated by existing authorities on application of the processes employed.

2. Risk Assessment Strategies

In studying hazards within any discipline, the risk is determined from the multiplication of the probability of an event by the consequence, which is applied in the IMO FSA process. In maritime navigation, events such as collision, grounding and foundering might be attributed to circumstances such as weather, equipment failure, integrity of available data or human error. Probability of an occurrence is dependent on factors that will include traffic, confines of the waterway and state of the vessel. Consequences of an incident include environmental damage, loss of life, personal injury and salvage costs, which will vary with severity of the incident and geography of the location in which it occurred. Assessment of risk in maritime navigation is therefore a complex task with universal measures requiring simplification of parameters through generalisation. A number of approaches have been developed, one is to apply spatial analysis in a Geographic Information System (GIS) environment. Existing bathymetry together with vessel traffic information and vessel data has been used in the USA by Ward and Gallagher (2011) and in Canadian waters by Chenier, Abado and Martin (2018). In both cases the purpose of the analysis was to prioritise hydrographic surveys, to improve safety of navigation at sea. Kiemola et al (2009) and Baksh et al (2018) have applied event trees directly through Bayesian networks where probabilistic models are combined within a network to assess risk relating to navigation. Other statistical approaches for determining likelihood of collisions and groundings are based on theoretical probability values for an event, given different types of encounter. Original work conducted and tested by McDuff (1974) and Fujii, Yamanouchi and Mizuki (1974) has been enhanced and developed into the the IWRAP computer application with further validation being undertaken (Friis-Hansen, 2008). In a broader context, the IMO offers a generic approach to FSA through application of event trees that lead from identification of hazards and consequences as indices, which are combined, to give risk as a score. The full FSA process then considers risk control options and associated cost-benefits to support the decision-making process for risk reduction. Computer implementation for determination of likelihood of an event through algorithms is an effective means of integrating spatial data, but generalisation of the input information is inevitable. There is then a need in the consideration of risk control options for qualitative review of computed risk with respect to the operational and environmental factors employed within the computer model.

In the case of the LINZ and IALA methods, the principles of FSA have guided their developments. The LINZ method was initially applied to Vanuatu (Riding et al, 2013) and has since been widely implemented in small island territories of the Pacific as well as New Zealand territorial waters (Caie, 2016). As with other approaches in the hydrographic domain, the primary purpose of the assessment is to evaluate chart adequacy, and hence to identify priority areas for charting. However, through implementation within a GIS environment the strategy incorporates numerous other factors associated with hazards and consequences to offer a broader assessment of risk in maritime navigation. Data sets are compiled on a grid to consider traffic density, navigational constraints, environmental factors and economic cost of an incident, with a weighted overlay approach adopted for integration. The process involves consultation with operators working locally to define weighting factors of the various data layers relevant for the study area. By comparison, the IWRAP software focusses on traffic management and better considers traffic flow through the application of statistical distributions of traffic across shipping corridors to assess risk of collision. Integration with bathymetry then allows interaction of vessels with the sea floor to be incorporated into the analysis. To ease causation analysis, implementation within IWRAP considers risk of collision and grounding separately. IWRAP is available commercially with workshops on principles and applications delivered to support users and as such is in regular use internationally, examples of application include Huang C., Tan K.W., Shibata (2017), Kim, Park and Park (2011), and Dzikowski and Ślączka (2014), Thanh N.X., Park, Y. and Park, J. (2012), Thanh.X., Park, Y. and Park, J., Jeong, J. (2013), Otoi O.S., Park Y., Park J (2016). In considering traffic flow, the IWRAP software is intended to meet the quantitative components of the IMO FSA scheme to determine likelihood of an event. IALA have separated this from the qualitative assessment, which is delivered separately through their Ports and Waterway Safety Assessment (PAWSA) scheme (IALA, 2009). Results from IWRAP would contribute to the risk assessment undertaken within a PAWSA process.

Both the LINZ approach to risk assessment and the IWRAP software were developed for specific purposes. The approaches are designed to be fully portable geographically for assessment of risk to navigation in areas of dense traffic or in confined waters, such as approaches to ports. In the case of IWRAP this is achieved through interactive software, while the LINZ approach is fully documented as a method for implementation in GIS (Riding and Rawson, 2015). Due to their differing strategies and intents, the resulting risk may not be directly comparable. The purpose of the LINZ approach is to produce a heat map across the entire waterway, which can be used to prioritise resources. IWRAP focusses on the shipping routes within the waterway, to assist in the decision making process regarding provision of aids to navigation services. Research presented in this paper considers the techniques used in each of these methods and results obtained within the Gulf of Paria in terms of the value of information provided to authorities with responsibility for aspects of risk management in relation to the IMO FSA scheme.

3. The Gulf of Paria

Sheltered waters of the Gulf of Paria have led to the development of port facilities shown in ***Figure 1*** serving the industrial island of Trinidad. As an oil rich nation, the offshore petro-chemical industry dominates the national economy with private terminals servicing refineries and a liquid natural gas shipping plant in Point Fortin. The national refinery is located at Point-A-Pierre with the coastal area between there and Point Lisas hosting various refineries and a cement factory all with private shipping facilities. A commercial deep water port at Chaguaramas provides a ship yard with services for offshore equipment and installations. Primary national ports in Port of Spain and Port Lisas with navigable depth of 12.5 metres operate container terminals and other cargo while another small national port with a separate channel in Port of Spain serves coastal vessels. The port of Port of Spain also offers passenger services across the Gulf to San Fernando, to Tobago and for cruise liners of the Caribbean. Private facilities are located at Brighton for various industrial cargo. In addition to the major ports, numerous marinas and quays exist for fishing and leisure craft. The Gulf is not a popular sailing location, but offers a haven for yachts of the Caribbean during the hurricane season. Large fishing vessels are rare, the fishing fleet consists primarily of countless small pirogues. The volume of traffic within the Gulf of Paria and diversity of operational interests in the marine space suggests that there is potential for a catastrophic event involving environmental impact to coastal wetlands and loss of life.

Deepest waters in the Gulf are about 30 metres with entrances to ports being maintained by dredging. The sea floor consists of sediments discharged by the Orinoco River in Venezuela, and to a lesser extent from the land mass of Trinidad to give a seabed of gently sloping soft mud. Consistency of the sea floor is less hazardous to a grounding situation, but blockage of a dredged channel for a period of time would have economic impact. Some ports function as trans-shipment to nearby territories, which would also be impacted economically. There is some internal traffic within the Gulf with the ferry service operating between Port of Spain and San Fernando crossing industrial traffic accessing ports in Point Lisas and Point-A-Pierre. Islands in the Dragon's Mouth to the north of the Gulf offer rocky shore lines. It is seen from ***Figure 1*** that most shipping follows this passage and then adhere to paths known to be clear from obstruction. In the restricted area shown in ***Figure 1,*** obstructions exist in the form of derelict and operational offshore platforms with numerous surface and sub-surface installations. Further hazards to navigation exist in the shallower waters along the coast in the form of obstructions of various types that are mostly uncharted and unmarked. The number of hulks identified by Valdez (2014) is 51, but realistically it is thought that the actual number runs into hundreds and continues to be a significant safety issue.

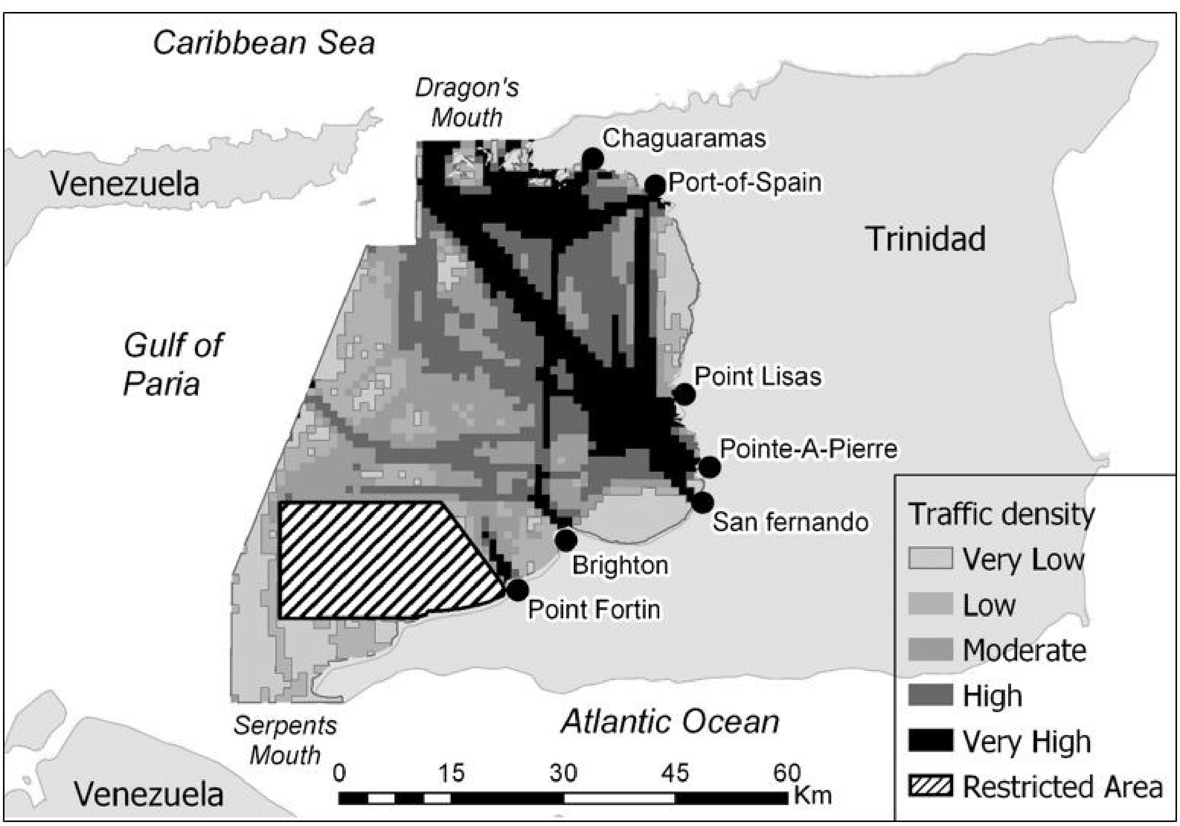


Figure 1. The study area in the Gulf of Paria, Trinidad with generalised shipping densities.

In addition to providing most of the major port facilities that maintain the economy of Trinidad and Tobago, the Gulf of Paria also offers space for recreation and nature. Beaches near Chaguaramas provide a recreational area where the government has made significant investment in construction of a boardwalk and maintaining the shore line. Waters around the islands of the Dragon's Mouth also offer recreational space and are home to unique black corals (Warner, 1981). Sites of national heritage and cultural interest existing on the shore include Waterloo Temple (Maharaj, 1996). The mangrove swamp at Caroni, immediately south of Port of Spain is protected under the Ramsar Convention (Jumar and Ramsewak, 2012), another substantial wetland exists near Brighton and mud flats along the shore line host wildlife. These areas of recreational, cultural and biological significance could be impacted significantly by the occurrence of an environmental disaster within the Gulf.

To assess shipping traffic within the Gulf a terrestrial Automatic Identification System (AIS) receiver was established at the University of the West Indies, 11 km inland from the Gulf of Paria, however at an elevation of 40 m it was found to cover at least the territorial waters of Trinidad and Tobago within the Gulf. Data collected for six months from July 2016 to December 2016 provided a database of 947 different vessels. AIS transmitters broadcast vessel status at regular intervals of a few seconds, another message giving vessel attributes is transmitted less frequently. Calder and Kurt (2009) explain how information provided by AIS is prone to human error with receivers requiring manual configuration for vessel attributes and status, a task that is often forgotten by watch keepers. Where possible, vessel attribute data were cross referenced using on-line data sources for vessels. Voyage data obtained from AIS includes vessel position, which is tagged with a unique vessel identifier. The overall track for each vessel constructed through time using the vessel identifier was broken into transits between points of departure and destination. The start and end transit was broken either by a change in status broadcast within the AIS message, or when the vessel position information indicated that it was stationary. Complete tracks for the 947 vessels produced 17,830 transits between points, the types of vessel and number of transits produced by each type is provided in **Table 1**. The types of vessel were reclassified from those adopted under AIS to combine some groups thereby further reducing the ambiguity in AIS data and discrepancies with vessel data obtained on-line. In spite of these efforts about 26% of the transits were made by vessels reporting their type inappropriately, most of which are likely to be small pleasure craft or work boats. ***Figures 2a through 2f*** show vessel tracks from commercial vessels of different types determined from terrestrial AIS data acquired.

Table 1. Number of transits made by vessels of different types.

Vessel Type (Original AIS)	Number of Transits	Vessel Type (Reclassified)	Number of Transits
Cargo	3367	Cargo	3367
Tanker	2690	Tanker	2690
High Speed Craft	1471	High Speed Craft	2141
Law Enforcement	58		
Military	33		
Pilot	579		
Passenger	476	Passenger	476
Tug	4357	Tug	4357
Pleasure Craft	11	Recreational	207
Sailing	196		
Other	3274	Other	4592
Reserved	500		
Reserved for future use	292		
Not available	526		

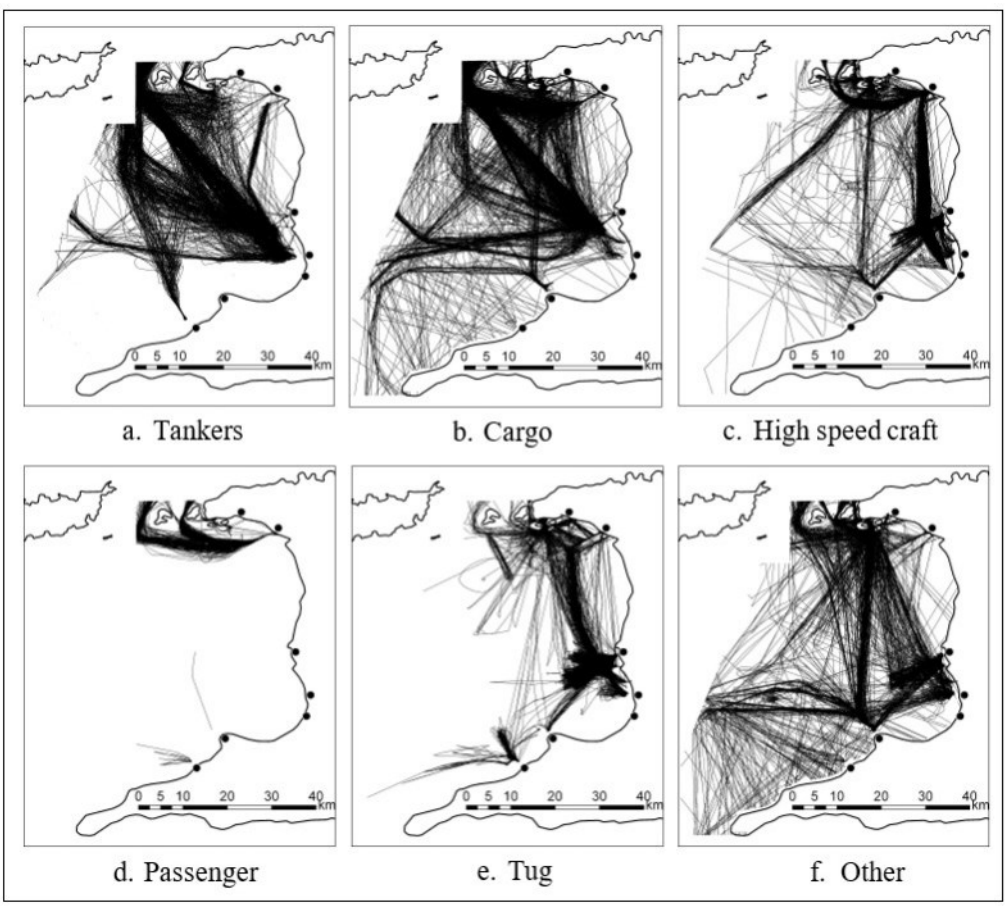


Figure 2. *Transits of different types of commercial vessels over the period of data.*

4. Implementing the LINZ method in the Gulf of Paria

Within the LINZ method the likelihood of an incident at sea is determined by considering vessel traffic density and hazards that could lead to loss of life and/or pollution. These consequences are then represented spatially and multiplied by likelihood with weighting factors to determine risk. Variables relating to likelihood and consequence are listed by category in **Table 2**. Within **Table 2**, the traffic density is listed separately as this impacts on both likelihood and consequence. Gross tonnage of vessel traffic across the study site is placed into a grid of vessels transiting that cell, shown as traffic density for the Gulf of Paria on a 1.5 km by 1.5 km grid in ***Figure 1***. ***Figure 3*** shows some of the data sets developed for the region impacting on likelihood and consequence, which are then placed on a grid of the same resolution as the vessel data. Age of the chart shown in ***Figure 3a*** varies across the region with the oldest surveys (Area 4) being conducted in 1925 and 1936 while surveys in Area 3 date from 1963. In the 1980's, surveys of the entrances to primary ports were carried out by a Hydrographic Unit (Holden, 1986) established for the purposes of conducting hydrographic surveys in Trinidad and Tobago waters. Charts covering Areas labelled 2 were produced locally and further survey data was also made available to charting authorities up until 1997. The most recent survey data incorporated in the charts was for the dredged channels into Port of Spain and Point Fortin under-taken by the US Navy in 2009. Channels are maintained at charted depth with compulsory pilotage for large vessels, otherwise there is little confidence particularly in shallow waters given visible uncharted obstructions and possible seabed dynamics, which is reflected in the risk level associated with chart quality. Bathymetry as depicted on the charts is extracted to determine navigational complexity with a grid containing levels for constrained navigation (along the shore line), port approaches (dredged channels) and three further levels defined by bathymetry. With channels in the Gulf dredged to 12.5 m, it is considered that the 15 m contour is significant because in deeper waters all vessels have freedom to manoeuvre. At some level in the region between the 15 m contour and the coastline, depth becomes a limiting factor on manoeuvrability of all vessels operating in the Gulf, therefore waters less than 15 m are shown in ***Figure 3b*** as greatest potential for a depth limited incident with buffers into deeper water indicating reduction. Hazards to navigation were obtained from the Energy Map of Trinidad and Tobago (NGC, 2017) and Admiralty Chart 483 produced by the United Kingdom Hydrographic Office (UKHO, 2005). The former offers the location of pipelines and other offshore installations while the latter shows the location of rocks, wrecks, oil platforms and navigational constraints. Vessels are at risk of collision due to the presence of isolated dangers across much of the study area as shown in ***Figure 3c.***

Met-ocean conditions also impact on the ability to manage the navigation of a vessel. Trinidad and Tobago Meteorological Service (2011) indicates that the probability of the Gulf of Paria being affected by a tropical storm is very unlikely and the relative risk to maritime navigation caused by prevailing wind and wave conditions is very unlikely. The whole region is in the lee of the island of Trinidad are sheltered from trade winds, although visibility is reduced at times by rain. Currents are also small, the Environmental Management Authority of Trinidad and Tobago (EMA, 2011) show currents at a velocity of up to 2 knots within the Gulf of Paria with little variation given the microtidal range. Each variable representing an aspect of met-ocean conditions is considered uniform across the study site.

Consequence is evaluated through spatial assessment of known features and vessel characteristics that impact on life and damage to the environment and to property contributing to the gross domestic product. Damage to the economy would be incurred through damage to the infrastructure and pollution events. Features under these categories given in ***Table 2*** are modelled within the GIS. Examples relating to environmentally sensitive areas are provided in ***Figures 3d, 3e*** for tourism and wetlands respectively with the implication that the closer an incident is to a feature the greater the consequence, hence buffer zones are applied. Pollution may also cause damage to fishing grounds, and as the whole of the Gulf is used for fishing a uniform measure was adopted. Areas with high economic contribution both regionally and nationally are also represented in the GIS as layers. Coastal infrastructure shown in ***Figure 3f*** includes offshore installations, fish landing sites and ports with data being digitised from the Energy Map of Trinidad and Tobago (NGC, 2017) and local mapping. Mitigation against economic cost of loss of life or property at sea is dependent on ease of search and rescue and salvage. Difficulty in search and rescue was obtained from the Trinidad and Tobago Coast Guard with cost of salvage of a vessel determined from representative cases internationally.

Spatial data for known dangers to navigation and safety measures such as navigational aids are available from the various data sources identified above, but effectiveness of the aids to navigation and chart quality (particularly in view of density of uncharted obstructions) are difficult to quantify from data. The risk assessment process requires consultation with professionals working in the study area either as mariners or in a support capacity, such as pilots and others working in maritime services. For the study of the Gulf of Paria such data was obtained by conducting a poll of professional opinion through a questionnaire. Likelihood and consequence criteria given in ***Table 2*** were provided with options to rank in the scale 0 to 5 in accordance with the scores listed in ***Table 2***. The questionnaire also asked local experts to express their opinion on weights for each category, and to rank the sub-category on a scale of 1 to 3 as low to high respectively. On this basis the sub-category weights are determined for the different layers within the data set as shown in ***Table 2***.

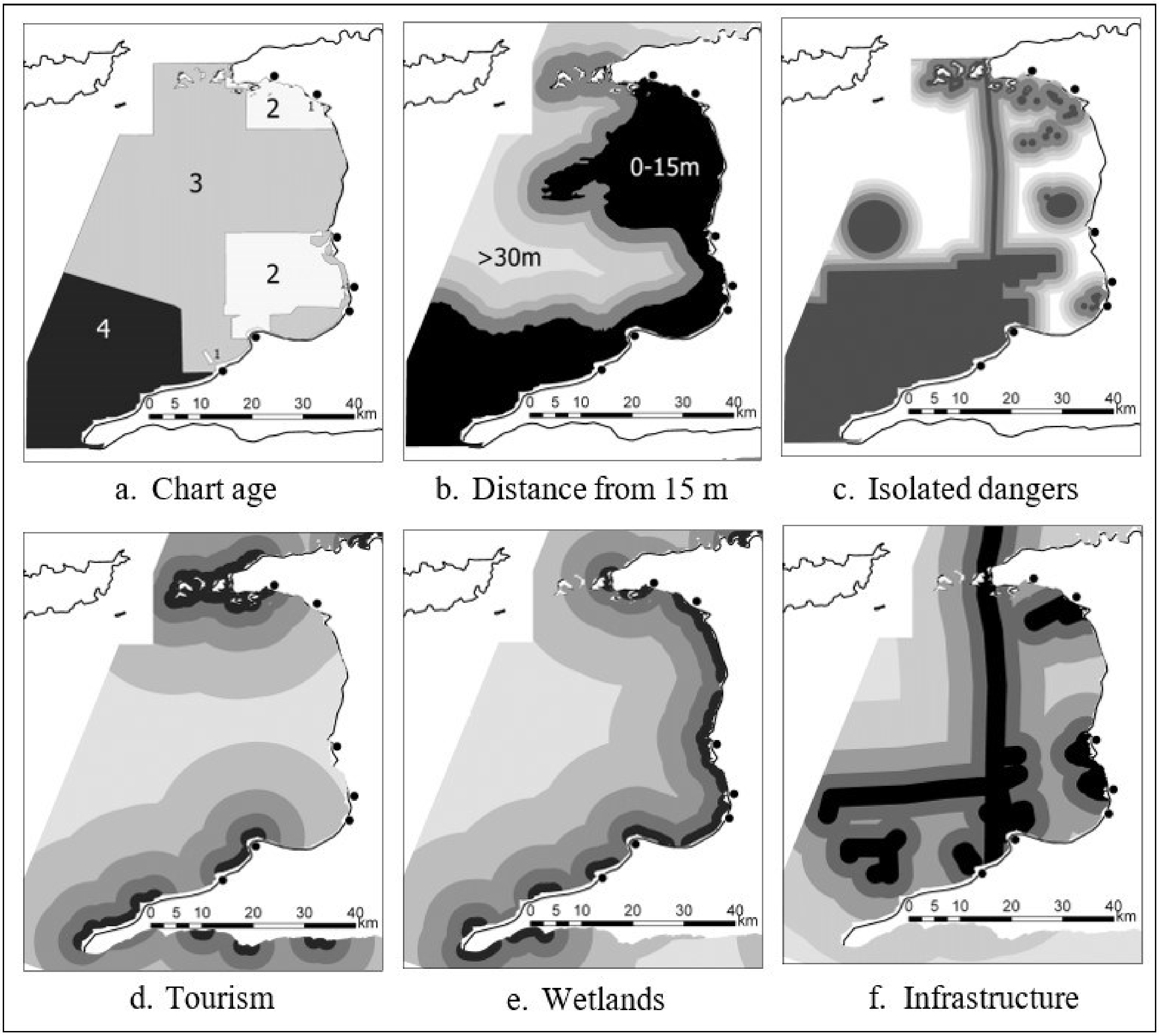


Figure 3. *Some of the hazards in navigation (insets a-c), environmental consequences (insets d-e) and economic consequences (inset f) .*

Table 2. *Data and weights applied to the Gulf of Paria using the LINZ model.*

Criteria	Category	Sub-category	Score 0	Score 1	Score 2	Score 3	Score 4	Score 5	Rank	Category Weight	Sub-category Weight
Vessel Traffic		Loss of Life	no risk	insignificant	low	moderate	high	catastrophic	N/A	N/A	0.5
		Pollution	no risk	insignificant	low	moderate	high	catastrophic			0.5
Likelihood	Chart	Detail	no risk	accurate	N/A	N/A	N/A	Inaccurate	3	0.16	0.052
		Age	no risk	≤5 yrs	5-10 yrs	10-20 yrs	20-30 yrs	> 30 yrs	3		0.052
		Quality	no risk	A1 or A2	B	C	D	E	3		0.052
	Route	Complexity	no risk	open sea	offshore	coastal	port	constrained	2	0.21	0.068
		Depth (15 m)	>10 nm	5-10 nm	2.5-5 nm	1.5-2.5 nm	1-1.5 nm	within 1 nm	3		0.103
		Traffic	no risk	insignificant	low	moderate	high	restricted	1		0.034
	MetOcean	Storms	no risk	very unlikely	unlikely	likely	more likely	most likely	1	0.21	0.034
		Poor Visibility	unknown	very unlikely	unlikely	occasionally	often	common	1		0.034
		Current	open sea	1-2 kts	2-3 kts	3-4 kts	4-5 kts	>5 kts	3		0.103
		Wind/Wave	no risk	sheltered	mainly sheltered	moderate exposure	mainly exposed	exposed on most days	1		0.034
	Hazards to Navigation	Dangers	> 2.5 nm	2.5-2 nm	1.5-2 nm	1-1.5 nm	500 m–1 nm	< 500 m	3	0.21	0.123

		AtoN effective	no lights	100%	80%	70%	60%	50%	2		0.082
	Mitigation	Pilotage	N/A	pilotage	N/A	N/A	N/A	no pilotage	2	0.11	0.105
	Seabed	UKC	N/A	N/A	N/A	N/A	N/A	inadequate	3	0.16	0.093
		type	N/A	soft				hard/rocks	1		0.031
		Dynamics	N/A	insignificant	low	moderate	high	significant	1		0.031
Consequence	Loss of life	Response	N/A	<60 nm	N/A	N/A	N/A	N/A	2	0.31	0.305
	Property	Salvage	N/A	<60 nm	N/A	N/A	N/A	N/A	3	0.16	0.155
	Proximity to sensitive area	Reef site	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	1	0.21	0.029
		Biological site	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	2		0.059
		Marine reserve	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	1		0.029
		Wetland	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	2		0.059
		Fishing ground	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	1		0.029
	Proximity to sites of economic impact	Channel	>2.5 nm	2.5-2 nm	1.5-2 nm	1-1.5 nm	500m – 1nm	<500 m	3	0.31	0.114
		High contrib.	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	1		0.038
		Coastal struct.	absent	Very low	Low	Moderate	High	Critical	1		0.038
		Cruise stops	>20 nm	10-20 nm	5-10 nm	2.5-5 nm	1-2.5 nm	<1 nm	1		0.038
		Pipe/Cable	>20 nm	5-10 nm	2.5-5 nm	1.5-2.5 nm	1-2.5 nm	<1 nm	2		0.076

Table 3: *Factors applied to transform a consequence to measures of pollution and loss of life.*

Vessel Type	Loss of Life Risk Multiplier		Pollution Risk Multiplier	
	Most Likely	Worst Credible	Most Likely	Worst Credible
Tankers	0.000005	0.00007	0.005	0.2
Passenger	0.00001	0.0017	0.000016	0.00085
Cargo	0.000008	0.00017	0.0015	0.0075
High-Speed Craft	0.1	0.7	0.00001	0.04
Tug	0.01	0.07	0.00001	0.04

Risk is defined as likelihood of an event multiplied by consequence (IMO, 2002). In the LINZ model documented by Riding et al (2013), the likelihood of an event (*L*) is scaled by the traffic density (*T*) and the consequence (*C*) by a factor (*F*) that transforms consequence to real world units of loss of life and quantity of pollution:

*Risk to Maritime Navigation = Traffic (T) * Likelihood (L) * Consequence (C)*Factor (F)*

Consequences are two-fold with loss of life and pollution being the concerns. An incident involving a passenger vessel has a greater potential for loss of life while an event involving a tanker would lead to greater pollution. Riding et al (2013) explain how event trees were used to consider scenarios leading to pollution and loss of life events. Using average vessel capacities for different types of ship, multipliers were determined to convert incidents to tonnage of pollution spilled and number of lives lost under most likely and worst credible situations, values are provided in ***Table 3***. An average value is then used as the multiplier for gross tonnage of vessels of different types, which offers a further complication as vessel tonnage is not incorporated into the AIS data structure and has to be sourced from on-line database sources. The potential for each of the two types of outcome from an incident is then computed from:

*Factor = Gross Tonnage * (Most Likely Multiplier + Worst Credible Multiplier) / 2*

The risk assessment process is implemented as shown in ***Figure 4***, using overlays of the various spatial data with weightings and factors applied to derive a risk map across the grid of the study area. Layers of gridded geospatial data initially are weighted according to the sub-category, this is done separately for likelihood and consequence criteria. Traffic is treated separately with gross tonnage passing through each cell being obtained for each vessel type as necessary for calculation of weighted consequences and likelihood. Finally, the product of scaled likelihood and factored consequence is formed to provide the risk model. The result for the Gulf of Paria is provided in ***Figure 5b*** in comparison with total gross tonnage provided in ***Figure 5a***, both are classified into five categories using the quantile distribution method. Risk is a relative measure and this process classified the risk into five categories as recommended under the IMO FSA process. ***Figure 5*** illustrates that high risk areas do not relate only to gross tonnage of vessel traffic, but integrates hazards and consequences. For example, while traffic is dense in the entrances to the ports the associated regions of heightened and significant risk exist in a wider area around the channels. In the Serpent's Mouth where there is a large volume of vessel traffic there is low to moderate risk and the reverse situation exists in regions in the middle of Trinidadian waters of the Gulf of Paria.

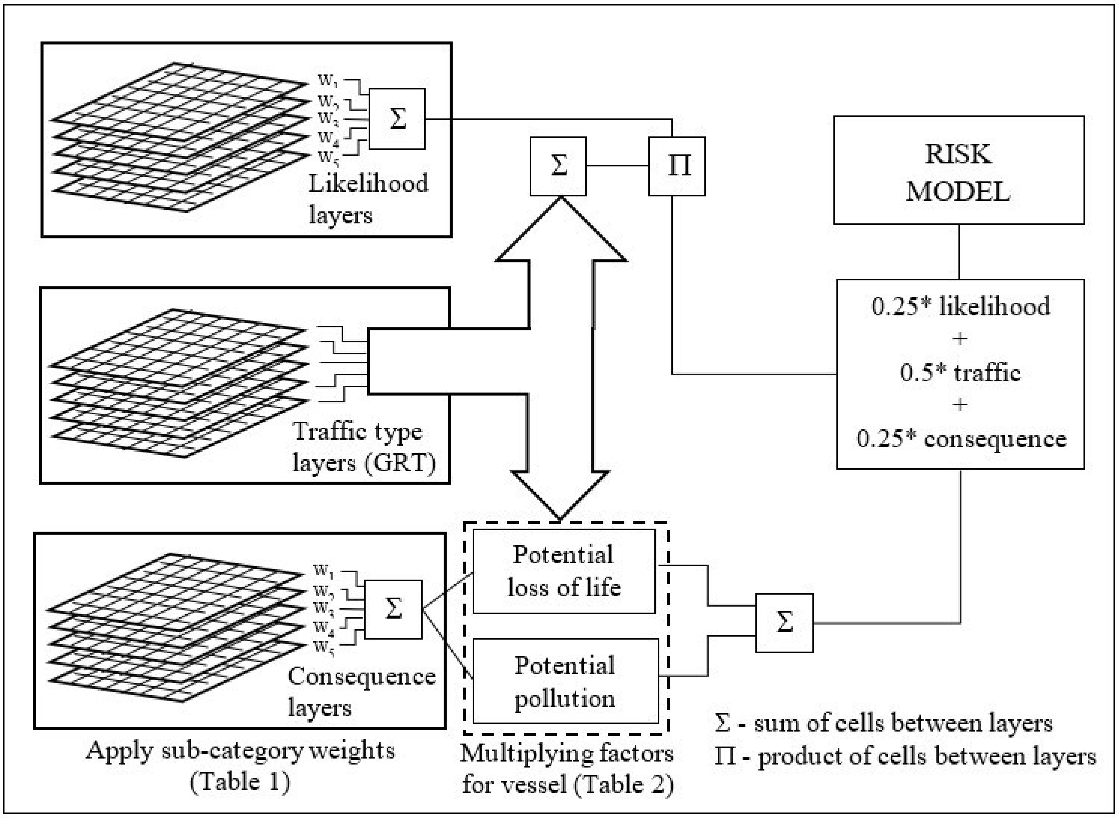


Figure 4. Computational process for the LINZ risk assessment

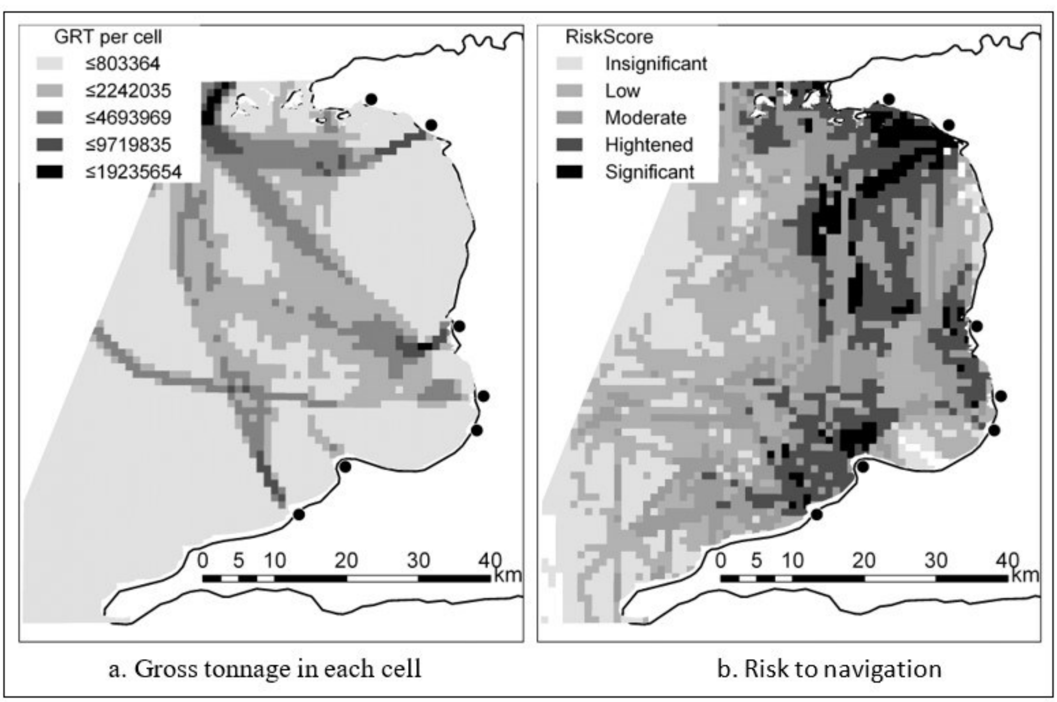


Figure 5. Vessel traffic and risk scores across the Gulf of Paria using the LINZ method.

5. Applying the IALA IWRAP software to the Gulf of Paria

IWRAP provides a rigorous statistical approach to probability of collisions and groundings. Distributions for vessel traffic along regularly used shipping routes are best extracted from AIS data, although they can be entered manually and this is necessary to introduce vessel traffic that does not carry AIS. Probability density functions are taken to be normal with mean and standard deviation computed from AIS traffic data. IALA (2019) documentation on IWRAP considers different types of encounter. Referring to ***Figure 6,*** the probability of a head on encounter for a pair of vessels drawn from two distributions is determined from equation (1) by intersection of the two normal distributions with parameters μ_i and σ_i for vessel type *i* travelling in one direction and μ_j and σ_j for vessel type *j* in the other. Vessel size must also be considered in assessing collision scenarios and average breadth is computed from the sample of vessels used to compute distribution parameters with data being provided within an AIS sentence. In equation (1), μ_{ij} is the distance between the means ($\mu_i+\mu_j$) for vessels of two types, σ_{ij} is the standard deviation for the joint probability distribution $\sqrt{\sigma_i^2 + \sigma_j^2}$ where B_{ij} is the average vessel breadth $B_{ij} = (B_i + B_j)/2$ and *N* indicates the normal distribution function. A collision can occur anywhere along the waterway, so the time each vessel spends transiting the channel must be considered. The number of encounters expected between vessels of type *i* and j (denoted E_{ij} in equation 2) depends on the length of the section of waterway being represented by these distributions (*L*.), speed of the different types of vessel (V_i and V_j) and number of passages of vessels of each type per unit time (Q_1 and Q_2) according to equation (2). This is summed over *i* and *j* for the different vessel types. The frequency of collisions between vessels per unit of time is then given by λ in equation (3). As the collision is a rare event due to the ability to perform an avoidance manoeuvre, the probability of a collision over some time interval Δt is estimated with an exponential by using a Poisson distribution as *P* in equation (4).

$$P_{ij} = N\left(\frac{B_{ij}-\mu_{ij}}{\sigma_{ij}}\right) - N\left(-\frac{B_{ij}-\mu_{ij}}{\sigma_{ij}}\right) \quad (1)$$

$$E_{ij} = L\sum P_{ij}\frac{V_{ij}}{V_i V_j}\left(Q_i Q_j\right) \quad (2)$$

$$\lambda = P_{ij}E_{ij} \quad (3)$$

$$P = 1 - e^{-\lambda\Delta t} \quad (4)$$

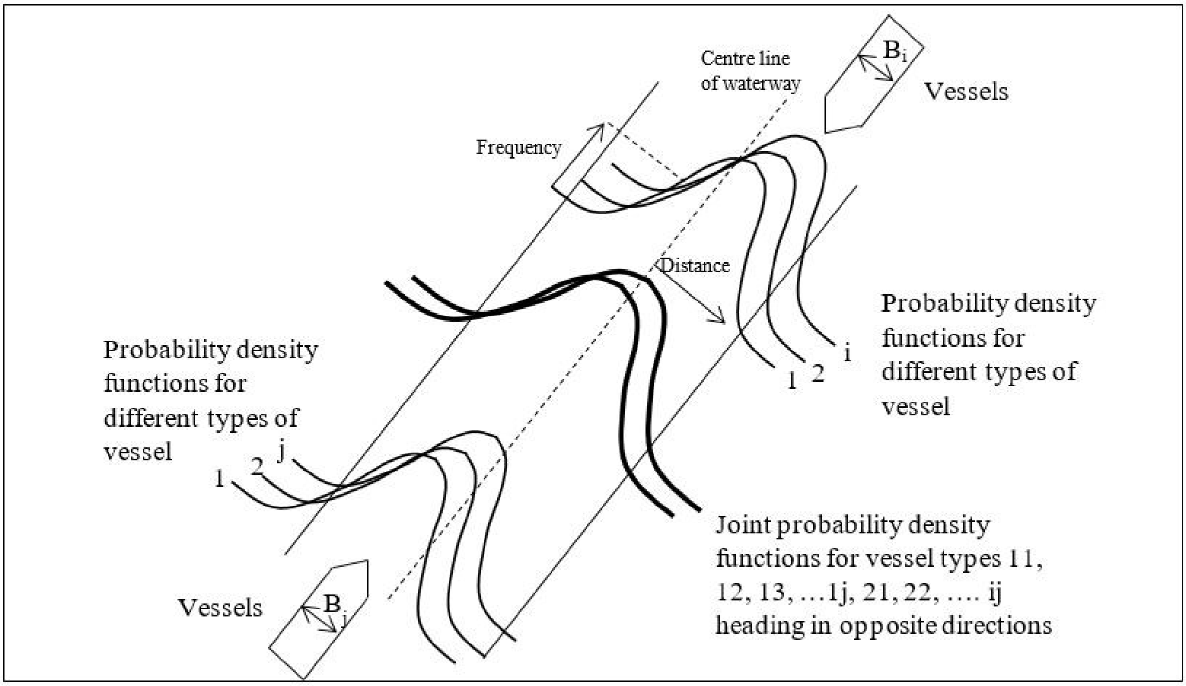


Figure 6. *Head on collision scenario between vessels in a channel*

For an overtaking encounter the same principles are applied with sign changes to accommodate similarity in direction of travel. Crossing and merging encounters require extension of the above to allow for angle of incidence between routes. Collisions with vessels on regularly used routes with those making irregular crossings are included by considering passages along cardinal and ordinal compass directions. The statistical distribution of irregular traffic is represented as uniform along the length of the route.

With the frequency distributions defined, probability density functions are computed from the theoretical foundation for different encounter types with causation factors. Thus, a spatial representation is available to provide probability values for the occurrence of a collision with factors being introduced to accommodate the human response to an impending incident. This is further enhanced through assessment of proximity of encounters based on AIS positions. Use of bathymetry derived from charted contours within the software further allows the computation to be performed with respect to grounding. Through user interaction the software allows impact of mechanical failure to be assessed, again this is achieved in statistical terms. The user enters the probability of such an event together with the distribution for repair time. The drift speed and direction under such an event is also set. Through simulation the possibility of mechanical or human failure is introduced.

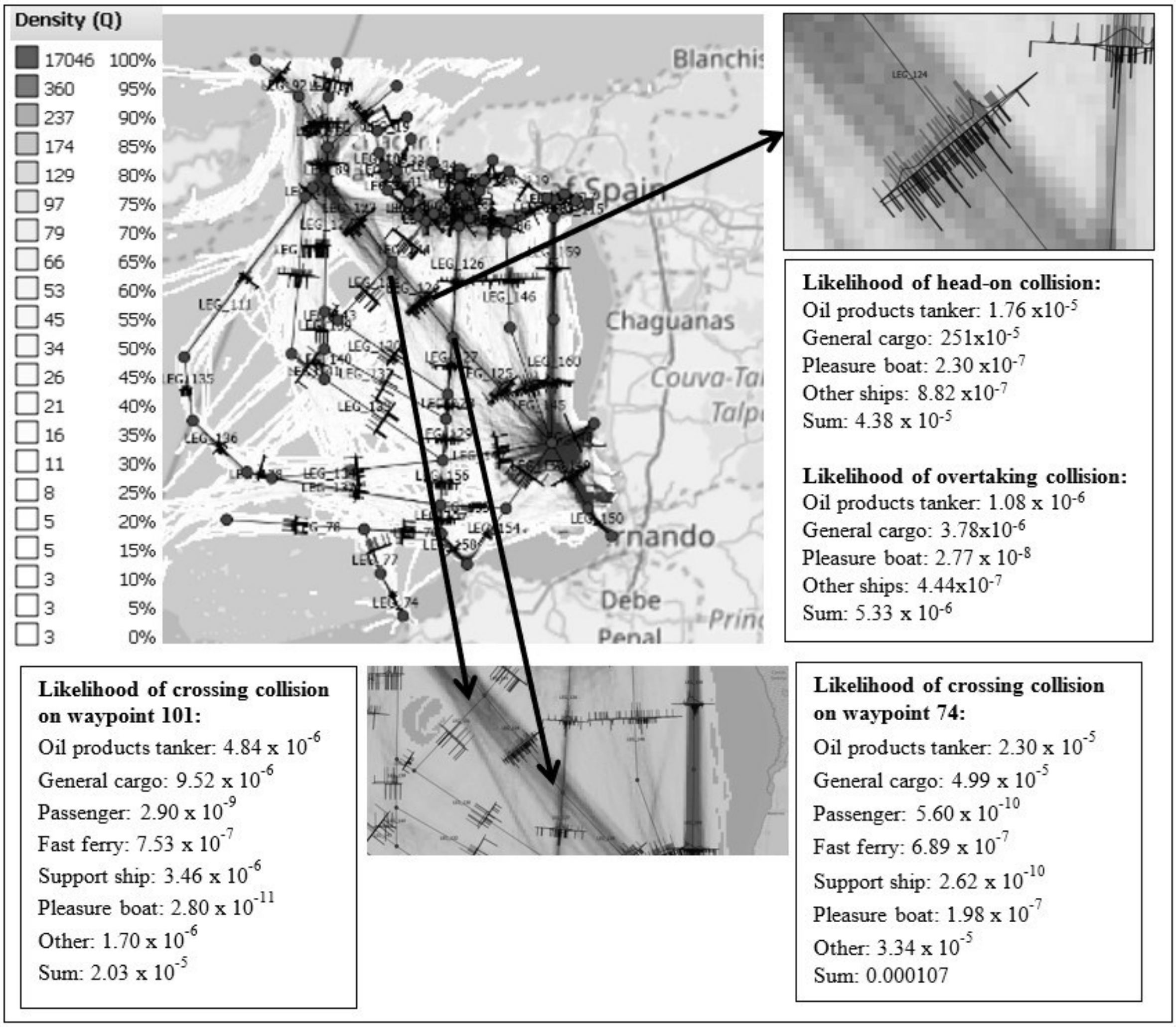


Figure 7. *Likelihood of head on, overtaking and crossing collision scenarios from IWRAP.*

The IWRAP software initially provides a traffic density chart shown in ***Figure 7*** where the legend indicates total number of vessels transiting a cell. Cell size is user selectable, the default value of 250 m was applied to produce ***Figure 7***. Traffic routes are identified within the density plot by joining waypoints selected manually at strategic locations along tracks of dense shipping traffic. The software produces a histogram of vessels transiting that route as extracted in ***Figure 7*** with bars on opposite sides of the section indicating direction of travel. Likelihood of collision of different types is then assessed according to vessel type as indicated in the three examples extracted within ***Figure 7***.

Compliance with the IMO FSA process is achieved by mapping likelihood determined from traffic analysis onto a five point scale. Results for the tracks defined in the Gulf of Paria are separated into encounters where tracks intersect (***Figure 8a***) and along tracks (***Figure 8b***). Relatively there is much less likelihood of a head on or overtaking collision along tracks than of a crossing or merging collision at an intersection of tracks. Probability of a collision is greatest at waypoints close to the ports and in the confined waters of passages between the islands to the North of the Gulf of Paria.

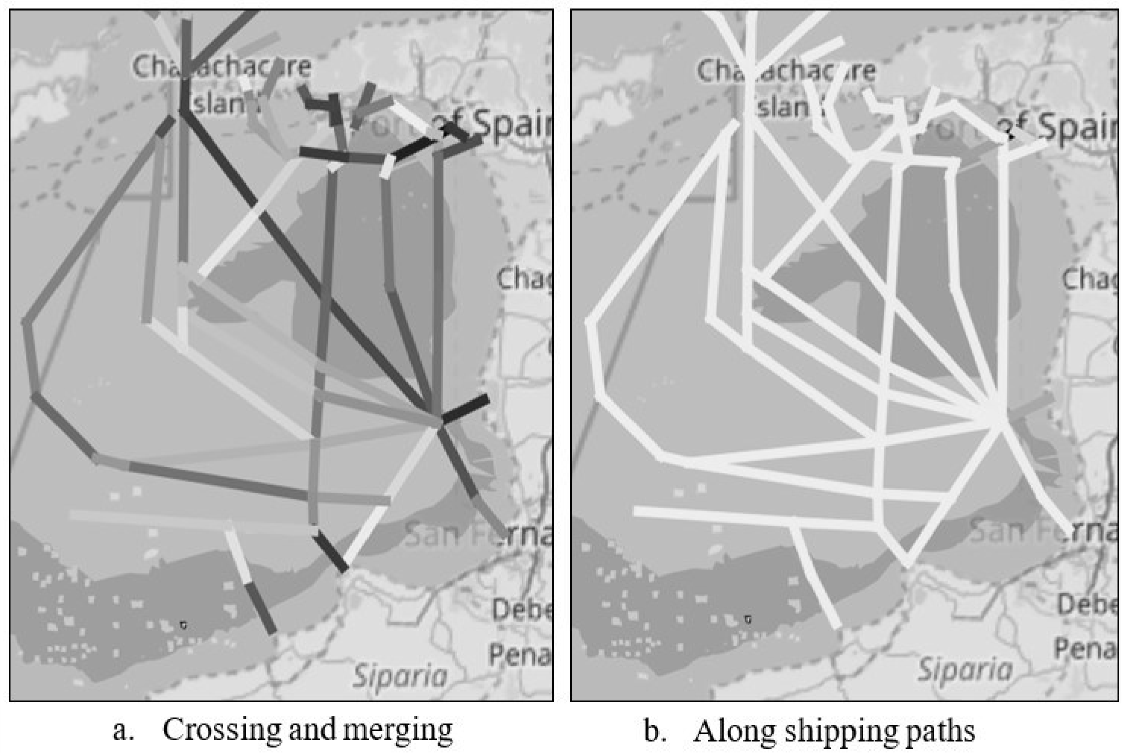


Figure 8. *Risk on user defined shipping paths in the Gulf of Paria from IWRAP.*

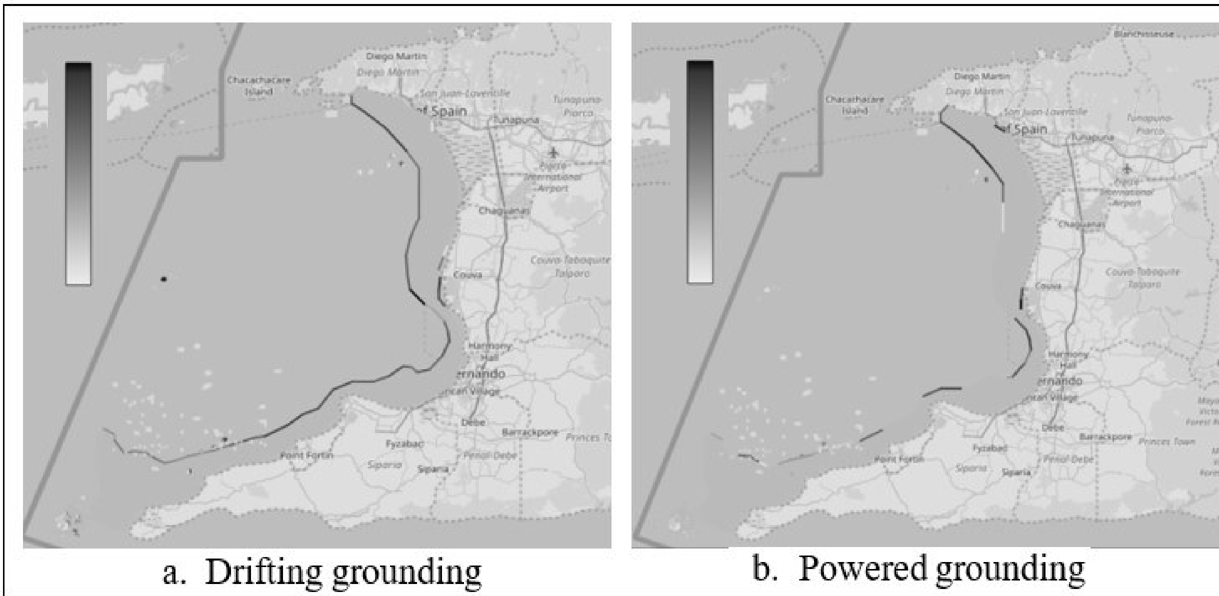


Figure 9. *Risk of grounding in the Gulf of Paria from IWRAP*

Risk of grounding by drifting or under power is assessed by considering vessel draught and bathymetry. In the case of drifting, the user interface of IWRAP enables entry of drift direction and speed. In ***Figure 9a*** the likelihood of grounding due to drifting is seen to largely follow a contour line of the bathymetry. For a powered grounding the vessels paths are extended towards the coastline with ***Figure 9b*** showing greater probability of such an event occurring in areas of high traffic density and along the coastline in areas where channels extend into the ports.

Powered Grounding	50.14	Years between incidents
Drifting Grounding	570.2	Years between incidents
Total Groundings	46.09	Years between incidents
Powered Allision	---	Years between incidents
Drifting Allision	2.037e+04	Years between incidents
Total Allisions	2.037e+04	Years between incidents
Overtaking	1,061	Years between incidents
HeadOn	322.3	Years between incidents
Crossing	1,182	Years between incidents
Merging	1.673e+04	Years between incidents
Bend	8,851	Years between incidents
Area	---	Years between incidents
Total Collisions	197.5	Years between incidents

Table 4. Summary of findings from IWRAP.

A final summary of likelihood from different types of encounter between vessels and the sea floor is provided in **Table 4**. Consequences of an incident are not considered within the software. However, with a probability chart and local knowledge of features such as coastline type and areas of economic or environmental significance as well as streams and currents, the consequences for different types of vessel can be considered externally to the software and the risk assessed. Results from the IWRAP assessment are considered with other safety measures within the IALA Port and Waterways Safety Assessment (PAWSA) scheme to provide a full risk assessment.

6. Discussion

It is evident that there is a lack of integrity in the source data acquired by the AIS, due primarily to failure of the operator to configure the transmitter correctly. It was necessary to obtain further particulars for vessels from on-line data sources including the IMO Global Integrated Shipping Information System (GISIS, 2019), MarineTraffic (2019) and Vesselfinder (2019). Through this process it was established that none of the databases are complete and nor are they available for full download. Furthermore, availability of data for a particular vessel is dependent on searching by the MMSI or IMO vessel number, which is occasionally erroneously entered into the shipborne transmitter with values such as 0 or a compliment of 1's or 9's being common. Transmitters are apparently reset on occasion, perhaps through power down with loss of signal and restart at some arbitrary position. Efforts to parse the data and construct transits for each vessel from continuous data streams for position were undertaken, initially through scripting of an automated procedure, which then required manual refinement. It is considered that the larger international vessels provide better data and the problems are more prevalent in the local traffic. Statistically, procedure, which then required manual refinement. It is considered that the larger international vessels provide better data and the problems are more prevalent in the local traffic. Statistically, the data available is representative of the vessel traffic in the region with some outliers due to erroneous AIS information having little impact on the overall assessment.

As satellite AIS data is dependent on satellite availability and increased possibility of conflict of data broadcast simultaneously by transmitters on multiple vessels as indicated by Carson-Jackson (2012), reliability is reduced in comparison with data acquired by a terrestrial receiver. Vessel tracks derived from satellite AIS data can have long segments between points, and the vessel may not have progressed along the straight line used to connect these points. In rigorous statistical assessment of vessel density along specified tracks, the IWRAP method for determining likelihood is best applied to terrestrial AIS data. In considering vessels transiting a cell of 1.5 km square, the LINZ approach is less susceptible to deviations from the true path introduced by linear interpolation between points when no data is acquired. However, this approach does not allow relative direction of vessels to be considered during encounters and the need for different equations for encounter types implemented in IWRAP suggests that this factor is significant in assessing likelihood of collision. Terrestrial AIS data was used for the risk assessment in the Gulf of Paria for both IALA and LINZ strategies.

The LINZ approach requires an extensive data acquisition and digitisation process with data being obtained from multiple sources across different disciplines. Weighting of the various risks and consequences under expert guidance proved a challenge. Many of the authorities with responsibility for managing the marine space from the government perspective offered politically correct responses to the questionnaire, with more pessimistic assessment being made by professionals operating in the study area. Some interesting insights were also gathered. During an interview, a retired Fleet Chief Petty Officer of the Trinidad and Tobago Coast Guard explained that, the lights on oil rigs are insufficient to prevent collision and Miller (2015) offers an example of a platform that exists outside of the restricted area shown on the Chart as lit, but is a derelict structure with tops of legs 6 m below the waterline. It is not appropriate to incorporate such anecdotal evidence and assumptions within a formal research agenda and the final likelihood criteria and weightings were implemented from responses to questionnaires with need for some interpretation using accompanying comments where diverse views were presented.

Units of risk associated with the final results provided by the LINZ model are relative. Likelihood for each grid cell is a value between 0 and 1 based on subjective criteria and does not formally consider the probability of a vessel being involved in an incident in a statistical sense. This value is multiplied by the gross tonnage of vessels passing through a cell. Consequence criteria given in **Table 2** is variable in relation to proximity to sensitive areas without consideration for currents that carry pollutants or a vessel in distress. A historical measure of impact in terms of pollution and loss of life for different vessel types by gross tonnage is further used to determine values in **Table 3** that relate vessel type to consequence. Without units being associated with these measures it is difficult to assess the results in an absolute sense, but relative risk is defined across the entire study area. Documentation for the LINZ method suggests that five categories be adopted based on findings with the upper quartile being used to define areas of highest risk. This approach enables classification of risk across the study area that identifies regions warranting further investigation towards implementation of mitigation measures. However, the results do not directly identify spatial attributes that lead to a high level of risk.

With appropriate training on the IWRAP software the IALA approach is simple to implement; IWRAP reads AIS data directly in raw form and accepts digital entry of bathymetry together with charted hazards. From initial graphical assessment of traffic, interaction through the user interface defines waterways and further analysis focusses on these areas. Likelihood is determined formally in terms of probability using statistical models and proximity of encounters adds information for interpretation. Simulations may then offer an assessment of risk reduction measures such as alternative vessel routing or separation. This offers a quantitative analysis for likelihood of an event that enables the frequency index defined by the IMO under the FSA approach to be determined on a five point scale. IWRAP does not consider the consequence, which is addressed in a second stage of an assessment under the PAWSA process. This would be administered by a questionnaire and site visit by third party experts to qualitatively consider consequence and hence determine a severity index that would combine with likelihood to give an overall risk assessment matrix. The PAWSA process will also be used to identify suitable mitigation strategies that would lead to risk reduction. Full documentation for a PAWSA process is provided by the United States Coast Guard (2019).

In the last sixteen years, there have been no incidents in the Gulf of Paria that have resulted in formal reports. Reports of oil spills in the social media are common (Clyne (2019) and Rodriguez (2020)) with containment measures being undertaken. Occasionally there is a small amount of pollution on beaches, but with the Guiana current flowing northward through the Gulf any uncontained spillage is carried out into the Caribbean Sea. Similarly, environmental incidents involving vessel traffic have never been of such significance as to involve formal reporting. A report by Hamilton-Davis (2017) in the local media documents the sinking of party boat “First Lady” that struck an unknown submerged object, fortunately there were only three crew on board and all survived. The problem of hulks and debris in the waters of the Gulf of Paria is well known with the matter being addressed in the Parliament of the Republic of Trinidad and Tobago (2014, pages 21/2). In 2009 and 2012, contracts were awarded to remove a total of 41 wrecks from the northern part of the Gulf of Paria at no cost to the government. This would have targeted hulks that were more easily salvageable for scrap value. A plan was called for with a view to removal of at least 100 additional wrecks (excluding small pirogues and fishing vessels) lying abandoned in Trinidad and Tobago waters at that time. Under the Public Sector Investment Programme (2018) of the Government of the Republic of Trinidad and Tobago, it is noted that for improvement to safety of navigation, 5 million TTD had been spent on removal of wrecks in 2017 and a further 6 million allocated for 2018. However, reports in the local media by Neaves (2018) and Singh (2018) identify the ongoing difficulty of abandonment of vessels in the Gulf and the associated dangers to navigation and the environment. As wrecks are located outside of regular traffic routes, this hazard is not covered by the IWRAP assessment. Within the broader scope of the IALA risk assessment programme, the problem may be identified under PAWSA as a concern for safety, but without undertaking surveys the scale of the problem is not known. Under the LINZ approach the risk in the area where the only known incident involving the sinking of “first Lady” occurred is classified as ‘moderate’ and may not be considered as high priority for charting.

7. Conclusions

In accumulating vast amounts of data and expert opinion for risk assessment the LINZ method is combining quantitative and qualitative information into a documented process to identify risk through application of GIS. The whole of a waterway is considered with multiple factors being introduced and integrated to determine a relative level of risk across the study area by considering likelihood and consequence. The IALA process distinguishes between likelihood and safety through IWRAP and PAWSA. IWRAP provides a rigorous statistical approach in the analysis of traffic on defined routes to present likelihood in those areas with PAWSA requiring expert opinion for further assessment of the results and review of the wider region. In compiling data for the LINZ model, much of the information that would be incorporated into the PAWSA programme is acquired. In the assessment of factors that contribute to risk, both processes rely heavily on opinion of experts. Professionals working in the region of interest are required to share their local knowledge with external parties with experience in risk assessment. In seeking local information specific to this study of the Gulf of Paria a diverse range of opinions were presented on existing hazards and their contribution to likelihood.

Using terrestrial or satellite AIS data for vessel tracks and other geographical information across the entirety of a waterway the LINZ approach is seen to reflect relative risk. One reported incident with an uncharted hazard causing a small vessel to sink was located in an area where risk is classified as moderate. While uncharted hazards are numerous in the Gulf of Paria, they are mostly located in shallow waters where consequences of loss of life and pollution are small. IWRAP has quantified likelihood of collisions and groundings within the regularly used passages within the Gulf of Paria. While there are no incidents for comparison, the rigour of the statistical strategy adopted based on a representative sample of traffic and bathymetry gives confidence in the results.

The strategies implemented through LINZ and IWRAP meet the objectives of the different purposes for which they are designed. IWRAP informs on likelihood of an incident in regularly used paths across a waterway, and hence identifies locations where aids to navigation would offer mitigation and risk reduction. LINZ considers a broader regional perspective. In the case of the Gulf of Paria, regions known to have a large number of uncharted hazards to navigation including the North between Port of Spain and Chaguaramas and East between Point Lisas and San Fernando are shown as moderate to high risk areas. Without specifically identifying hazards in these areas within the input data the process has identified significant risk. The requirement for charting is not so much the need for bathymetry, but rather for identification of hazards. There is no formal mechanism in either of the IWRAP or LINZ methods to identify the primary causation factors contributing to areas of significant risk. Ideally a risk assessment would incorporate both approaches to inform on risk followed up with a PAWSA process to consider findings and develop strategies for mitigation.

With the availability of terrestrial AIS data the IWRAP software offers an immediate visual representation of traffic and through the user interface the likelihood of collisions and groundings in the high traffic areas can be quantified. However, the LINZ approach has demonstrated that for the Gulf of Paria these are not necessarily the areas of most significant risk. IALA would identify such areas through the PAWSA scheme as an assessment report that has been incorporated within the LINZ risk assessment method. The complex procedure with multiple spatial variables is time consuming to implement in a GIS, worsened in cases such as Trinidad where there is a scarcity of readily available digital data. There would be significant benefits in integrating these approaches to offer a staged process to risk assessment. Initially, the use of IWRAP as an initial inspection tool, then to undertake a qualitative assessment report through expert consultation that identifies hazards, consequences and potential mitigation methods. This offers data for implementation of the LINZ method that is able to assimilate the multiple spatially varying data sets and finally to test mitigation strategies using IWRAP and LINZ approaches.

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9. Authors biographies

Dawn Seepersad is an Advisor to IALA and a PhD student in the Department of Geomatics Engineering and Land Management at the University of the West Indies in Trinidad and Tobago. Her research is entitled: An Economic Evaluation of Risks due to Maritime Navigation across the Greater Caribbean Region. Her research is being supported by the Commonwealth Marine Economies Programme. Prior to commencing her research, Dawn was a GIS intern at Land Information New Zealand, where she worked on the Niue Hydrographic Risk Assessment. Dawn holds a BSc. Geomatics Engineering (Honors) and a MSc. Geoinformatics (Distinction). E-mail: dawn@seepersad.org

Omar Frits Eriksson is the Deputy Secretary General of IALA and the Dean of the IALA World-Wide Academy. Omar contributed to the creation and development of IWRAP Mk2. He has 30 years of experience of Managing Aids to Navigation services and has chaired IALA technical committees such as the e-Navigation and the Engineering Committee for decades. Omar has a degree in telecommunication and has a master's degree in Management of Technology and Innovation from the Technical University of Denmark. He is also a visiting professor at Jimei University in Xiamen, China. E-mail: omar.eriksson@iala-aim.org

Adam Greenland is National Hydrographer at Land Information New Zealand (LINZ), the New Zealand Hydrographic Authority (NZHA). He holds a Merchant Navy Deck Officer certificate of Competency, a tertiary qualification in Hydrographic Surveying and Mapping Sciences, and is a Member of the Royal Institution of Chartered Surveyors. Adam has previously held roles at the Port of London Authority, UK, which included Deputy Port Hydrographer.

Keith Miller is a Senior Lecturer in the Department of Geomatics Engineering and Land Management at the University of the West Indies in Trinidad and Tobago. He delivers courses in relation to Geodesy and Hydrography within a BSc programme in Geomatics and undertakes research in these disciplines. Keith is a Member of the Chartered Institution of Civil Engineering Surveyors and is a former Member of the International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers.



Articles

SATELLITE WATER COLUMN DATA FOR HYDROGRAPHY
Hydrographic Survey Implications of Vortex-Induced Turbidity in Optical-Band Satellite Imagery

By H.F. Stewart[1], R. van de Poll[2] and K. Brumley[3]
[1] *Fugro, Houston, Texas, USA*
[2] *Fugro, Fredericton, New Brunswick, Canada*
[3] *Fugro, Houston, Texas, USA*

Abstract

Optical-band satellite images selected for satellite-derived bathymetry (SDB) analysis require clear water with low turbidity. As a result, image selection processes exclude images with excess turbidity regardless of cause.

Images with water-column turbidity contain valuable information. Under certain conditions, vortex patterns in navigable waters are present in satellite imagery. Although vortex-induced turbidity excludes these images from SDB processing, the presence and shape of these vortices contain information relevant to hydrography. In this observational study, we use two case studies to describe vortex patterns and environmental conditions leading to their formation and then explore novel hydrographic survey applications of these phenomena.

Keywords: Satellite imagery, coastal zone dynamics, hydrographic survey, vorticity, survey planning

Résumé

Les images satellitaires en bande optique sélectionnées pour l'analyse de la bathymétrie dérivée par satellite (SDB) nécessitent une eau claire et de faible turbidité. Par conséquent, les processus de sélection d'images excluent les images présentant une turbidité excessive, quelle qu'en soit la cause.

Les images qui montrent la turbidité dans la colonne d'eau contiennent des informations précieuses. Dans certaines conditions, les images satellitaires montrent des tourbillons dans les eaux navigables. Bien que la turbidité induite par les tourbillons exclue ces images du traitement SDB, la présence et la forme de ces tourbillons contiennent des informations pertinentes pour l'hydrographie. Dans cette étude basée sur l'observation, nous utilisons deux études de cas pour décrire les configurations des tourbillons et les conditions environnementales qui ont conduit à leur formation, puis nous explorons de nouvelles applications de ces phénomènes pour les levés hydrographiques.

Mots-clés : Imagerie satellitaire, dynamique des zones côtières, levé hydrographique, tourbillon, planification des levés

Articles

Resumen

Las imágenes satelitales de banda óptica seleccionadas para el análisis de batimetría derivada de satélites (SDB) requieren agua clara con una baja turbidez. Como resultado, los procesos de selección de imágenes excluyen las imágenes con exceso de turbidez, independientemente de la causa.

Las imágenes con turbidez en la columna de agua contienen información valiosa. En determinadas condiciones, los patrones de vórtices en aguas navegables están presentes en las imágenes satelitales. Aunque la turbidez inducida por los vórtices excluye estas imágenes del procesado SDB, la presencia y la forma de estos vórtices contienen información relevante para la hidrografía. En este estudio de observación, utilizamos dos estudios de casos para describir los patrones de los vórtices y las condiciones ambientales que llevan a su formación y luego exploramos nuevas aplicaciones de estos fenómenos a los levantamientos hidrográficos.

Palabras clave: *Imágenes satelitales, dinámica de las zonas costeras, levantamiento hidrográfico, vorticidad, planificación de levantamientos*

1. Introduction

Hydrographic surveyors use a wide variety of data acquisition tools and methods to collect, analyze, and characterize information about the survey area environment. These tools and methods may be quantitative in nature, such using multibeam sonar soundings to derive depths, or they may be qualitative, such as observing that a sediment sample contains brown sand.

Satellite-based optical-band (400-700 nanometers) images allow discovery and analysis of qualitative and quantitative information in areas and at scales that cannot be easily detected by the unaided human eye. The comparatively low cost and wide area coverage of satellite imagery is a valuable complement to ship-based or airborne surveys, particularly in areas with no recent data or from data of suspect quality. Repeat flyovers by satellites at regular intervals allows for change detection analysis at a given location, which is useful to determine whether a new survey is needed or whether an observed feature is real or image noise.

When analyzing optical-band satellite imagery for hydrography, there are three broad questions we can ask:

- What is the shape of the water bottom (seafloor morphology)?
- What is the thickness of the water column (bathymetry)?
- What relevant information is present and observable in the water column?

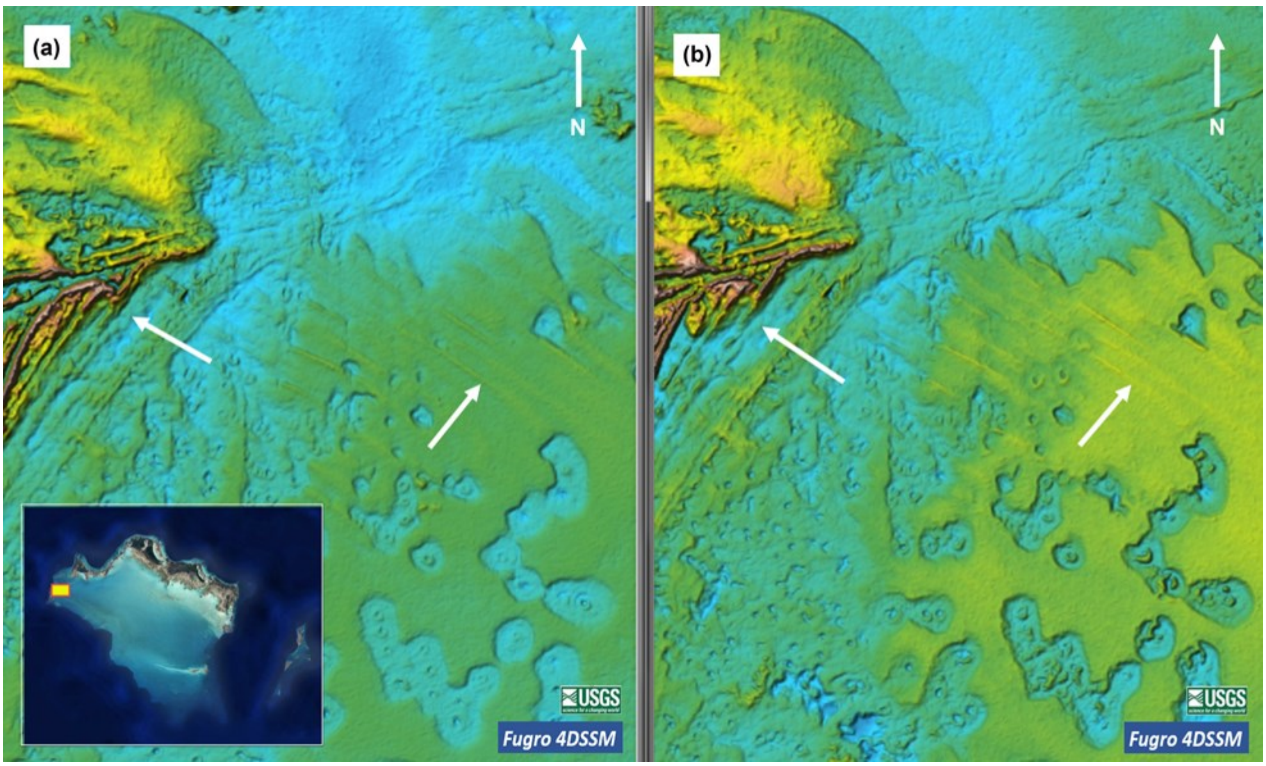
Satellite-derived bathymetry (SDB) is a quantitative image analysis method used to determine water depth – the thickness of the water column – at the time of the image. SDB analysis requires optically clear water with calm seas, minimal aerosol interference (e.g., clouds, dust), low sun-glint, and minimal surface obstructions (e.g., vessels). Water column turbidity may cause false detections or limit the utility of any individual image. As a result, images with high turbidity are typically not considered for SDB analysis regardless of the cause.

Images excluded from SDB processing due to turbidity do have value, however, as they may contain information on the seabed or water column that can be analyzed in other ways. Band analysis on multispectral satellite images is used to detect and delineate kelp beds or harmful algal blooms (Schroeder et al, 2019). Optical-band imagery from the RapidEye satellite has been used to evaluate temporal variation in suspended sediment concentration in rivers in Brazil (Soares et al, 2019). The presence of kelp or floating algal mats in the former and high levels of suspended sediment in the latter demonstrate the value of water column data in optical-band satellite data in aquatic environments – even though images from kelp beds in western Canada or muddy rivers in Brazil would not be considered candidates for SDB analysis.

Fugro 4DSSM is a qualitative data visualization technique that is designed to make information in a satellite image or series of images more visually intuitive to a trained human observer. It is used to assist geologists in interpreting seabed bedforms for Law of the Sea projects (van de Poll, 2004 & 2018) or other private-industry survey projects in which absolute knowledge of bathymetry is not required. Although individual scenes appear similar to a bathymetric Digital Terrain Model (DTM) or a Digital Elevation Model (DEM), Fugro 4DSSM is not a bathymetric product.

Fugro 4DSSM images are always analyzed as a time-series to determine true seafloor morphology from image noise and ephemeral data, using the principle that real seabed objects occur in the same place 100% of the time. Figure 1 shows an example of how Fugro 4DSSM is used to examine geologic features in two 4DSSM scenes based on Landsat-8 Panchromatic band images of West Caicos, Turks and Caicos, acquired 4 years apart. White arrows point to subtle bedforms that have persisted during that time, even after a direct strike in 2017 by Category V Hurricane Irma.

Figure 1: *Fugro 4DSSM scenes of West Caicos, Turks and Caicos, based on Landsat-8 Panchromatic band images. White arrows point to subtle bedforms. (a) Source image acquired 8 January 2014. (b) Source image acquired 21*



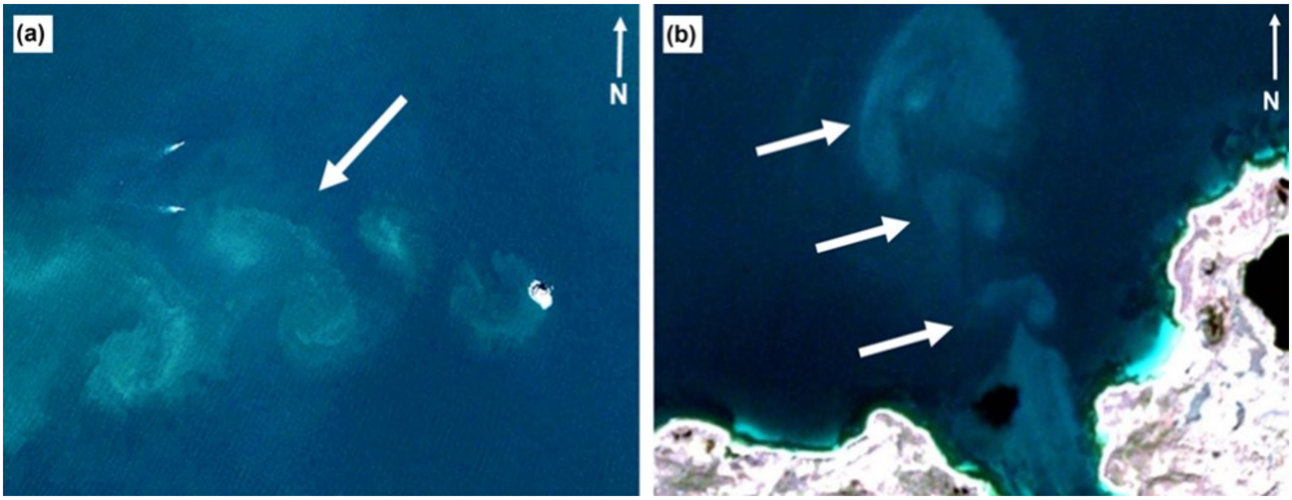
December 2018.

In a fortuitous finding, the authors discovered that in addition to making seabed morphology visually obvious, converting Landsat-8 source images into Fugro 4DSSM scenes made vortex structures in the water column in those images visually obvious.

Vortices are regions in a fluid in which the fluid flow rotates around a central axis. Vortex features in navigable waterways are classified according to size: mesoscale (10-200 km), sub-mesoscale (1-10 km) and microscale (10 m – 1 km). Mesoscale and larger sub-mesoscale (> 2 km) vortex features are unlikely to be found near coastlines and are unlikely to impact nearshore safety of navigation and engineering surveys.

Smaller sub-mesoscale and microscale features found in navigable waterways are more likely to be of interest to hydrographers. There are two primary types of sub-mesoscale or microscale vortices observed in satellite imagery that are of interest to safety of navigation projects: Von Kármán vortex streets and vortex dipoles. Von Kármán vortex streets are a visually distinctive set of counter-rotating vortices that propagate downstream of a seabed feature and rotate *inwards* relative to direction of current. Vortex dipoles are counter-rotating paired vortices whose direction of rotation is *away from* the central axis of the source current. ***Figure 2*** shows examples of both types of vortex patterns.

***Figure 2:** Vortex patterns visible in turbid water in satellite imagery. (a) Maxar Worldview-4 image of a Von Kármán vortex street (white arrow) in coastal waters of the Republic of Korea. (b) Sentinel-2 image of a series of vortex*



dipoles (white arrows) in coastal waters of Massachusetts, USA.

This paper examines two case studies in which sub-mesoscale and microscale vortex features are observed by inspection of optical-band imagery from Sentinel-2 and Landsat-8 satellite images: one in Saudi Arabian waters of the Arabian Gulf, and one in coastal waters of the Republic of Korea. We describe common factors leading to vortex formation and discuss how these common factors inform hydrodynamic studies and hydrographic survey planning. Finally, we make recommendations for future study of these vortex features in the context of hydrography.

Throughout this paper, qualitative information about water column vorticity is examined and analyzed in the context of necessity and sufficiency. It is *necessary* for an object to be a shipwreck to be classified as a hulk on a nautical chart, but not sufficient (wrecks may be fully submerged or awash). It is *sufficient* to be a shipwreck lying on shore to be classified as a hulk, but not necessary (hulks need not be onshore). Qualitative information that is *sufficient* to determine hydrographic significance helps surveyors save time, effort, and money by doing intelligent survey planning and by avoiding needless effort, especially when making decisions related to the safety of vessels and their crews. In some cases, qualitative observations are sufficient to perform chart evaluation or chart updates, such as observing during a post-hurricane survey that a fixed aid to navigation is destroyed. Although the hydrographic survey applications of observed vortex activity in both case studies are generally qualitative, they are sufficient for use in different aspects of hydrographic survey practice.

2. Methods

Source Images

Source images for both case studies are acquired by the United States Geological Survey (USGS) Landsat-8 and European Space Agency (ESA) Copernicus Sentinel-2 satellites. Publicly available source images were obtained from the USGS website https:\\earthexplorer.usgs.gov.

The Landsat-8 satellite, which occupies a near-polar orbit at a mean orbital altitude of 705 km above nominal sea level, obtains optical-band imagery from the Operational Land Imager (OLI) instrument. Radiometrically calibrated, orthorectified Level 1 Terrain Precision Correction (L1TP) images were selected to cover the entire Area of Interest (AOI) for both case studies (USGS, 2017). Band 8 (Panchromatic, 500 – 680 nm) images were used at their native 15 m resolution. Bands 2 (450 – 510 nm), 3 (530 – 590 nm), and 5 (850 – 880 nm) were used at their native 30 m resolution to create false-colour Red-Green-Blue (RGB) imagery of areas of interest.

The ESA Copernicus Sentinel-2 mission consists of two satellites, Sentinel-2A and Sentinel-2B, carrying identical payload instruments at a mean orbital altitude of 768 km above nominal sea level and operating in orbits separated by 180° (ESA, 2015). The primary imaging payload instrument is the Multi Spectral Instrument (MSI), which obtains images in 13 spectral bands. Images from both Sentinel-2A and Sentinel-2B satellites were used. Orthorectified Level-1C image tiles were selected to cover the entire AOI for both case studies. Bands 2 (central wavelength 443 nm), 3 (central wavelength 560 nm), and 4 (central wavelength 665 nm) were used to created false-colour RGB images of the AOIs. Band 3 images at their native 10 m resolution were used for Fugro 4DSSM scenes.

Source images from both satellites are georeferenced in fixed cartographic geometry using World Geodetic System of 1984 (WGS84), projected into the plane in Universal Transverse Mercator (UTM) coordinates for the appropriate longitude of the Area of Interest (AOI); this is the native georeferencing system for images from both satellites.

3. Image Selection

Image selection was performed by human users based on the following criteria:

- Presence of visible vortices in the water column
- Less than 20% total scene cloud cover

The following criteria were considered for image selection only in the context of whether vortices were visible or not:

- Water colour variations observed in RGB imagery
- Water clarity
- Sun glint
- Surface noise from wave action
- Dark-coloured seabeds (such as seagrass areas)
- Man-made surface obstructions (such as oil and gas structures or floating oyster rafts)
- Localized aerosols (such as flaring-off at offshore oil and gas structures)
- Turbulence-induced turbidity not associated with vortex activity (such as vessel wakes)
- In the Arabian Gulf AOI, aerosolized dust (as interpreted from RGB false-colour images)

In the Arabian Gulf AOI, images from the months of July and August – the summer Shamal Wind season – were excluded from consideration due to high likelihood of excess aerosols.

For Landsat-8 images, percent land cloud cover and nadir/off nadir was not considered. For Sentinel-2 images, orbit direction (ascending or descending) and satellite (Sentinel-2A or Sentinel 2-B) were not considered.

4. Image Analysis

Images for each AOI were catalogued according to satellite, date of acquisition, and time of acquisition. In the Arabian Gulf AOI, approximate phase of tide information for each image was obtained by correlating astronomical predicted tidal curves derived using the British Admiralty Simple Harmonic Method with the timestamp of the image, using the position of a single feature of interest as the benchmark location. Because this study is observational in nature, phase of tide was catalogued solely to assess variability in vortex shape over time and no attempts to compute absolute tidal height or water depths were made.

ESRI ArcGIS Pro was used for inspection and analysis of images. One map scene was created for each AOI. For simplicity, coordinate reference frames of the ArcGIS map scenes were chosen to match the native coordinate reference frames of the source images – WGS 84 UTM Zone 39 North for the Arabian Gulf AOI and WGS84 UTM Zone 52 North for the Republic of Korea AOI. Navionics Electronic Nautical Charts (ENCs) in GeoTiff format were loaded into the map scenes and converted from native coordinate reference frame into the map scene reference frame.

Red-Green-Blue false colour composite images were created using GlobalMapper software, using the band selection described previously. RGB images were then exported into GeoTiff format and added to the relevant ArcGIS map scene.

Images that were found by inspection to have good examples of different vortex morphologies were converted into Fugro 4DSSM scenes. Source images from Landsat-8 Band 8 (Panchromatic) or Sentinel-2 Band 3 images were converted to Fugro 4DSSM scenes using Blue Marble GlobalMapper and Teledyne CARIS LOTS software, using only visualization tools available in those commercial-off-the-shelf software packages (no proprietary algorithms or software add-ons are used). Because Fugro 4DSSM is solely intended to present geomorphology and water column structures in a visually intuitive manner, and is not a bathymetric product, 4DSSM images are presented without colour scales to prevent misinterpretation.

Case Study 1: Vortex Streets, Arabian Gulf, Kingdom of Saudi Arabia

Study Area Background

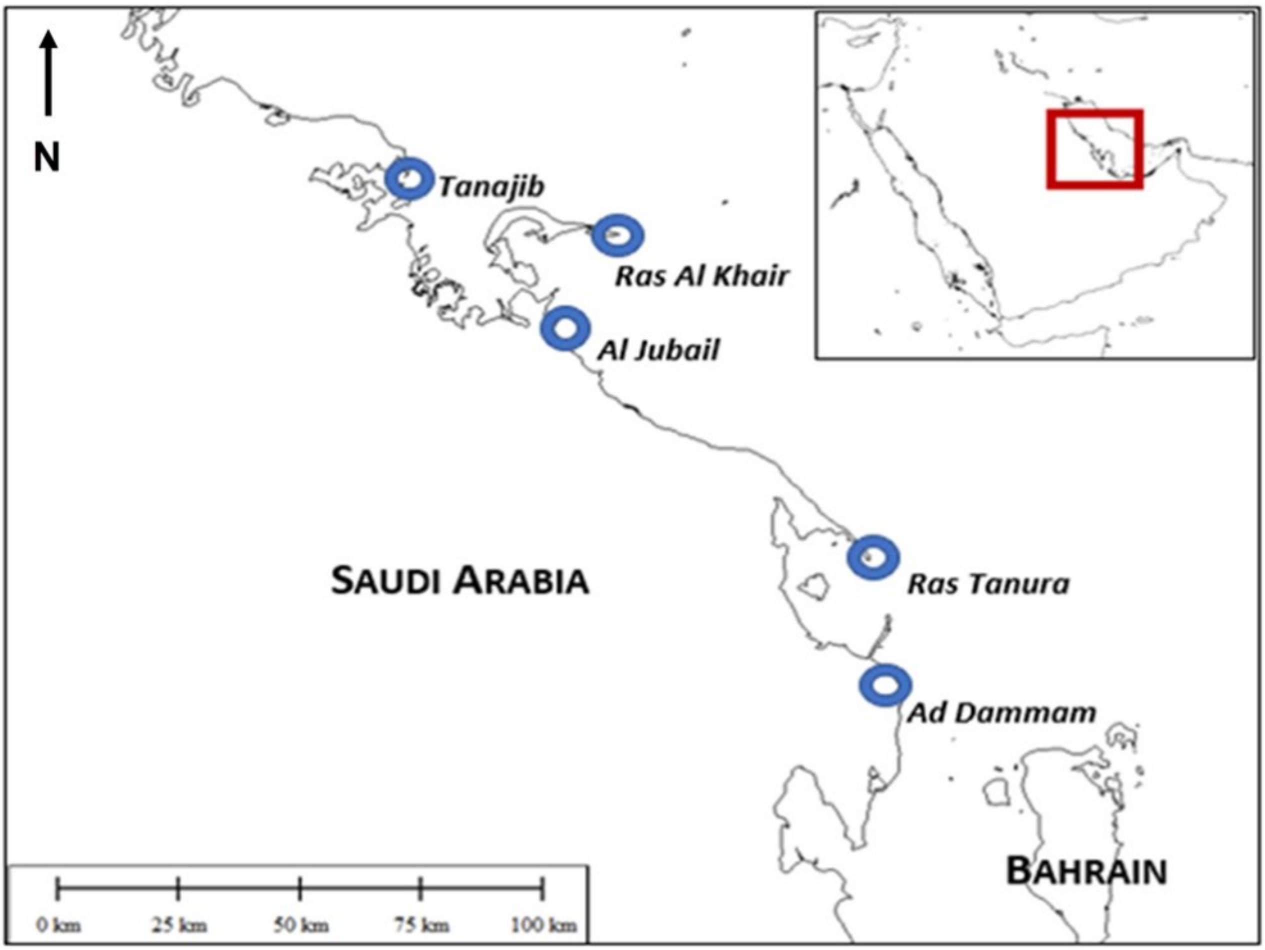
The city of Ad Dammam, Kingdom of Saudi Arabia, is home to the largest of a group of seaports serving the oil and gas industry along the Arabian Gulf coast from the Bahrain Causeway to the ports of Tanajib, Ras Saffaniyah, and R'as al Khair. (***Figure 3***).

Waters in this region are warm and optically clear, with a shallow shelf less than 60 m deep that ranges between 28 and 60 km from shore. Sediment type ranges from coarse to fine sand with scattered coral heads and rocky reefs occurring throughout the region. Because of the heterogeneity of seafloor features in this area, both oscillating turbulent wakes and vortex streets are present in the Arabian Gulf study area.

Figure 3: *Case Study 1 – study area with blue circles showing the location of port cities along the coast of the Arabian Gulf, Kingdom of Saudi Arabia. Map outlines from World Maritime Boundaries v.11.*

Von Kármán Vortex Streets

Wake flow patterns around bluff (non-streamlined) obstructions are described by the Reynolds number (***Re***), a dimensionless ratio of inertial forces to viscous forces within a moving fluid with



different internal fluid velocities. For general cases, the Reynolds number is written as:

Equation 1.

$$Re = \frac{uD}{v}$$

Where *u* is the speed of the current, *D* is the diameter of the bluff obstruction, and *v* is the kinematic viscosity of the fluid. In general, as Re increases, the wake downstream of the bluff obstruction will change as shown in ***Figure 4***.

Figure 4: *(1-6): Six regimes of constant fluid flow past smooth circular cylinders. (1) and (2) represent laminar flow, indicative of low current speed or small cylinder diameter. (3) and (4) represent laminar and partially laminar Von Kármán vortex streets, with degree of turbulence increasing with current speed. (5) Disorganized, fully turbulent bubble wake. (6) Fully turbulent vortex street with no laminar properties. Adapted from Lienhard (1966)*

An example of a Von Kármán vortex street behind a stranded shipwreck is shown in ***Figure 5***.

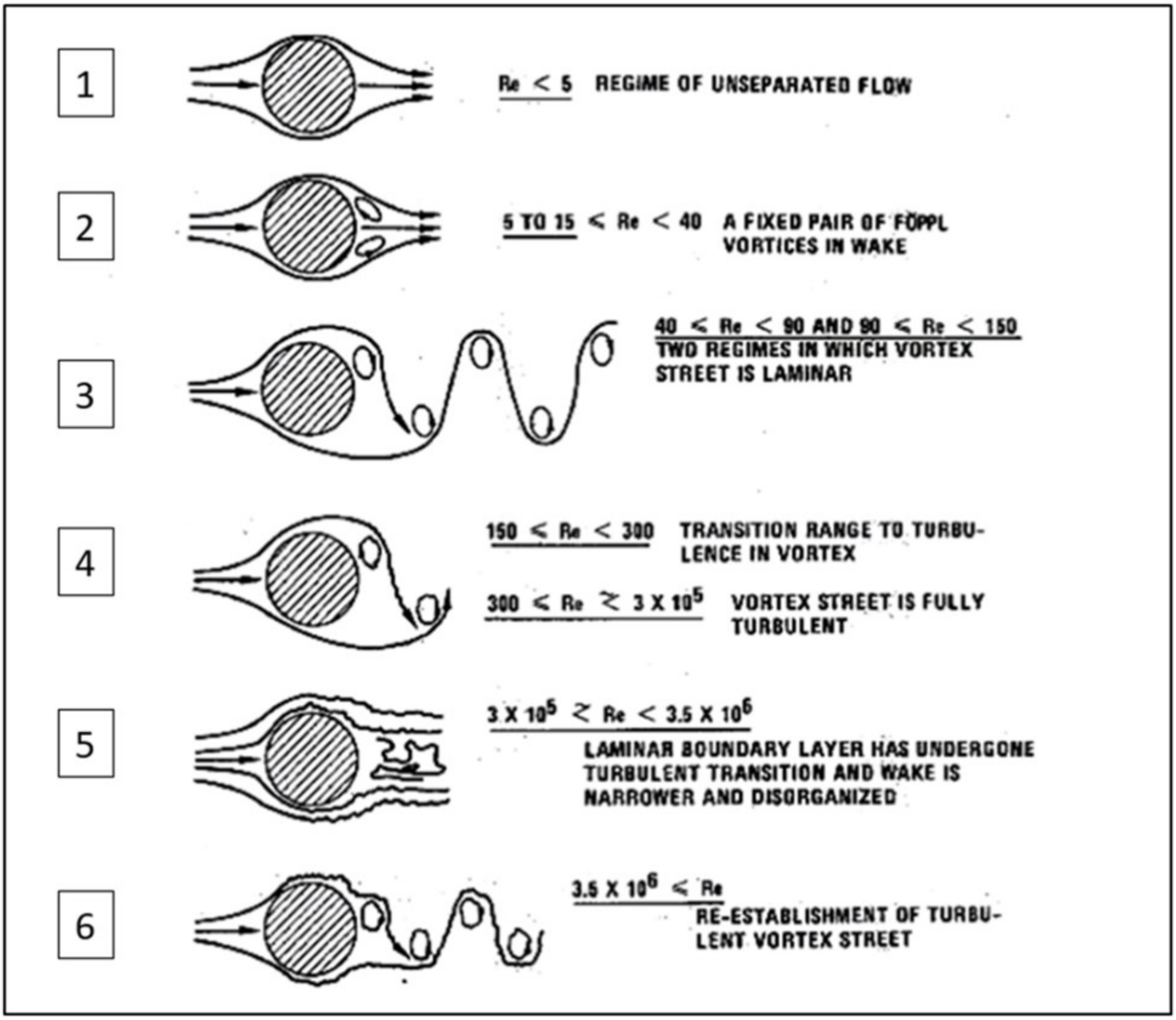


Figure 5: *Von Kármán vortex street in Landsat-8 image dated 21 February 2019, Port of Ad Dammam, Saudi Arabia. Hulk image credit: D. Rostopshin, shipspotting.com.*

In coastal ocean environments, wakes form around islands, coral heads, shipwrecks, and other natural and anthropogenic features that are firmly fixed to (or part of) the seabed. The effects of bottom friction on the ratio between friction forces and inertial forces becomes significant, and the

general-case Reynolds number must be revised to account for this. The Reynolds number for small islands (***Re***^{s}) is given as follows:

Equation 2.

$$Re^s = \frac{uH^2}{A_v L}$$

Where *u* is current speed, *L* is the cross-current diameter of the island, *H* is water depth, and A_v is a coefficient of vertical-direction turbulent viscosity (Tomczak, 1996).

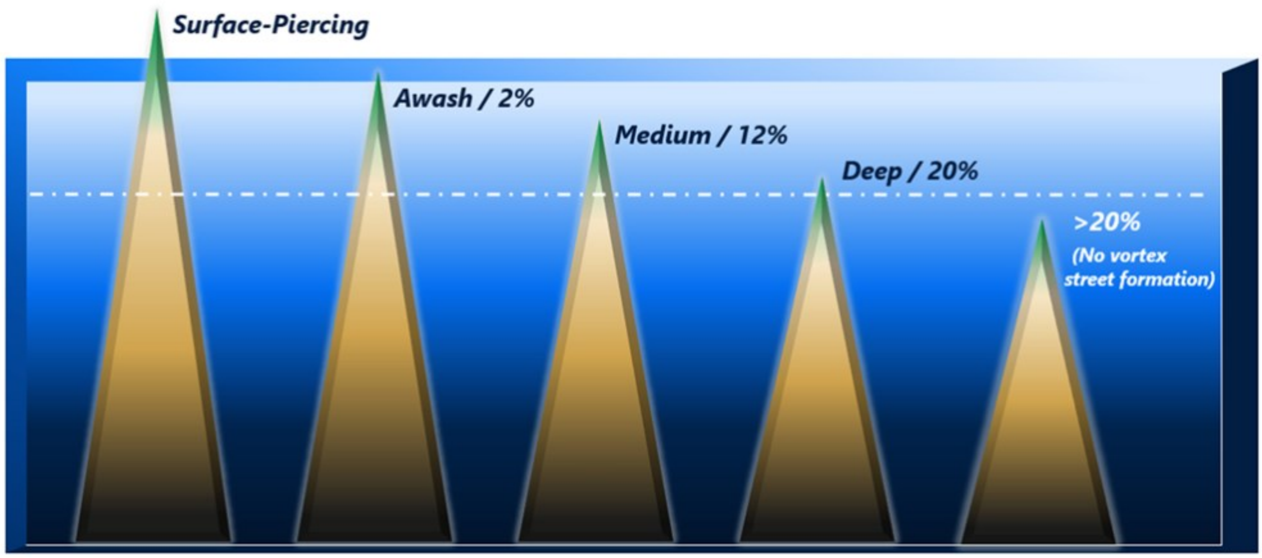
It is beyond the scope of this paper to explore methods of determining A_v. It is sufficient to recognize that both current speed and water depth are significant factors in vortex street formation, and that observing a vortex street in sea water is sufficient to confirm the existence of a seabed feature.

Vortex street morphology as a function of submergence

Lloyd and Stansby (1997a, b) used experimental models to demonstrate that a causal relation-ship exists between the shape of vortex streets behind seabed features and the submergence of the body, where submergence is defined as the ratio of flow depth *H* to object height *h*. Their model generated turbulent wakes using simulated conic islands or seamounts in water flumes at different submergence values from surface-piercing (*H/h* < 1.00 to *H/h* = 1.20). ***Figure 6*** is a onceptual diagram that depicts relative submergence of a conical island.

Figure 6: *Conceptual diagram of submergence level H/h*

Turbulent wakes were observed by injecting dye into the water flow up-current of the simulated



islands/pinnacles. Observations were used to populate 2D and 3D numerical model simulations. In all experimental runs and model simulations, as submergence increased, the strength of vortex shedding decreased and the distance from bluff obstruction to the first shed vortex increased. Eventually, vortex activity disappeared entirely as water was able to flow over the top of the model bluff obstructions. ***Figure 7 (a-d)*** shows surface current vector fields of model islands at different levels of submergence.

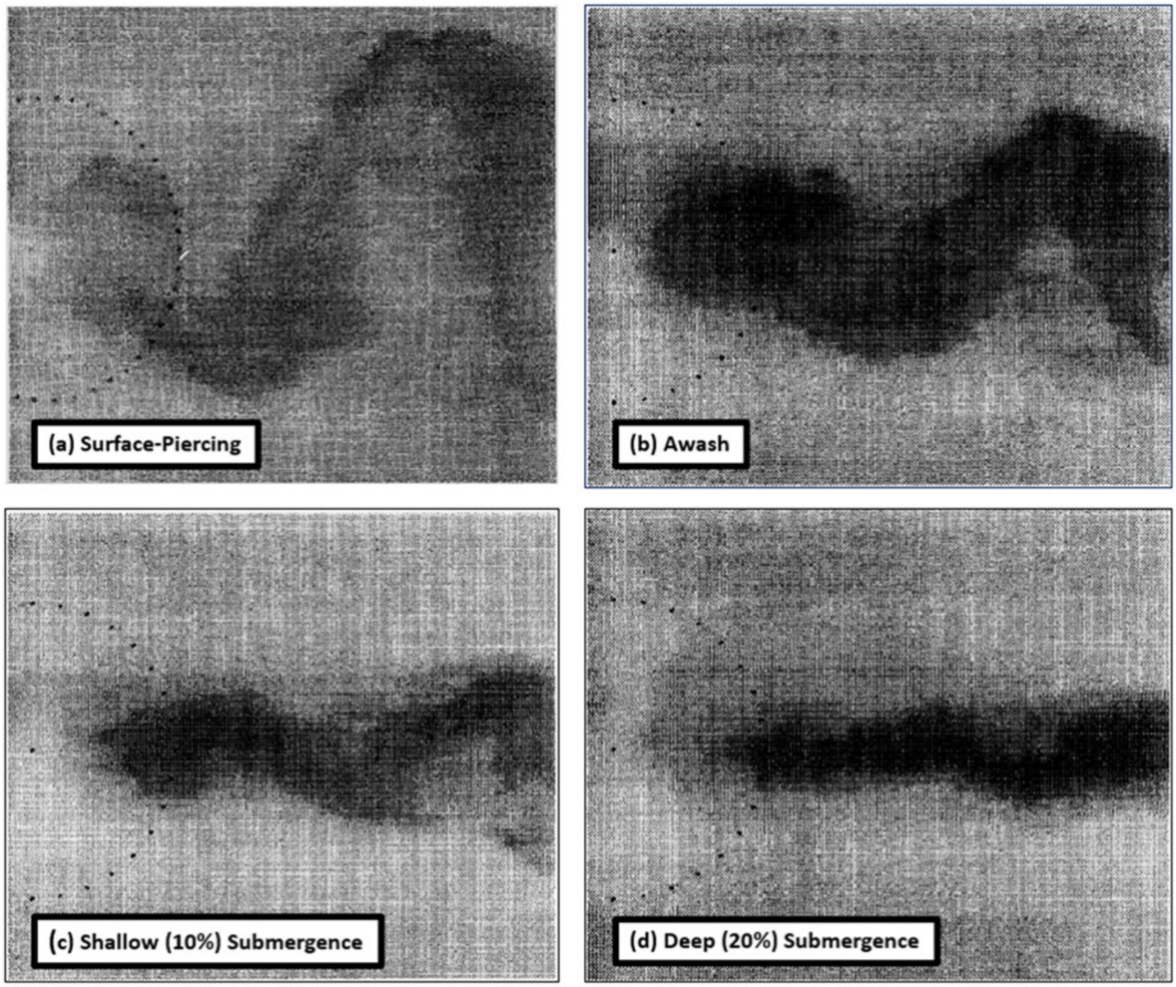


Figure 7: *Surface current vector fields of conical islands at different submergence levels and resulting changes in vortex activity. 7 (a): surface-piercing island, from Lloyd and Stansby (1997 a). 7 (b), (c), (d): conical islands at varying degrees of submergence, from Lloyd and Stansby (1997 b).*

Vortex streets at different submergence levels in the Arabian Gulf study area

Numerous vortex streets downstream of bluff obstructions are present in a single Landsat-8 OLI image dated 21 February 2019. Fortuitously, this image was acquired near low tide, and multiple vortex streets with different morphologies are observed to form downstream of seabed features.

Using the Navionics Electronic Nautical Chart (ENC) of the area to estimate feature and seabed depths and calculate submergence ratios *H/h*, we compare observed vortex street morphology with the experimental presentation of turbulent vortex wakes described by Lloyd and Stansby (1997 a, b) as illustrated in Figure 7. Using these comparisons, we demonstrate that vortex street presence and morphology is sufficient to make a qualitative assessment of nautical chart accuracy. Note that here, “obstruction” refers to “obstruction to flow” and does not imply that a feature is an obstruction as used in nautical chart notation.

Surface Piercing Vortex Pattern

An example of a Von Kármán vortex street can be observed in the approach to the port of Ad Dammam (See ***Figure 3*** for location), propagating down-current from an exposed charted hulk measuring 140 m in length and 18 m beam at approximate position 26 ° 33' 32" N, 50° 12' 27" E. The relative position of the wreck is shown in Figure 8a and charted notation in ***Figure 8b***.

In the Lloyd and Stansby (1997 a) **surface-piercing** model (or *H/h* = 1.00), vortex shedding begins immediately downstream of the obstruction and the wake width at the first shed vortex is greater than the diameter of the obstruction (Figure 8d). The measured distance across the vortex street starting at the first shed vortex is 270 m, over 100 m wider than the cross-current length *L* of the wreck (Figure 8c), which concurs with the Lloyd and Stansby model.

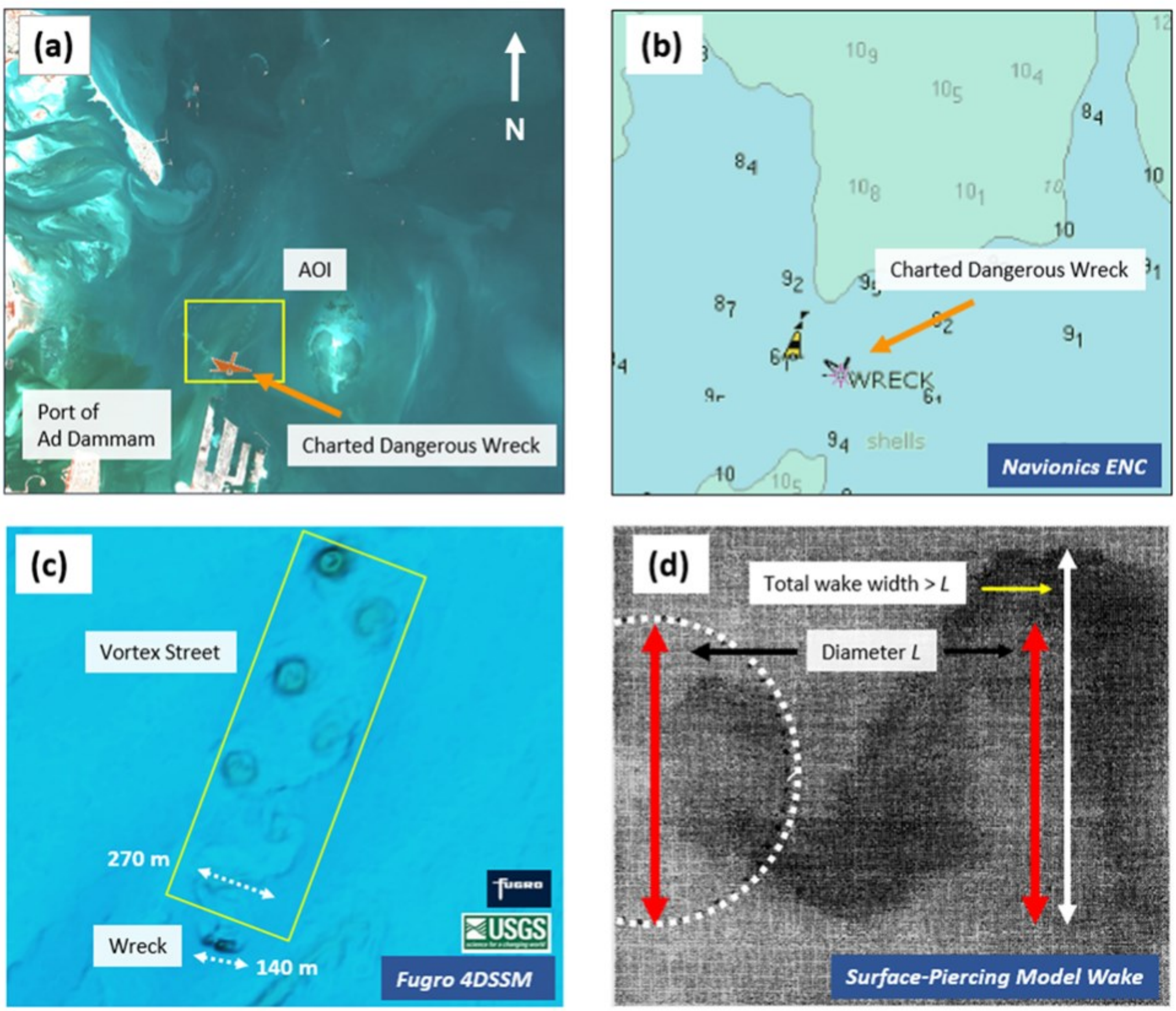


Figure 8: *Wake structure comparison for a charted dangerous wreck in the approach to Ad Dammam, Saudi Arabia. (a) Landsat-8 image of Port of Ad Dammam, showing relative position of the wreck introduced in Figure 5. Yellow box is location of (b) Navionics ENC confirming that the wreck is surface-piercing. (c) Fugro 4DSSM scene of the shipwreck, vortex wake, and measurements showing that wake width (270m) from the first shed vortex exceeds the shipwreck length (140m). (d) Lloyd and Stansby (1997a) model wake of surface-piercing conical island, showing Diameter L (red arrows) and white arrows shows wake width increase in L.*

Awash Vortex Pattern

For the purposes of this paper, seabed features are defined to be awash if they are less than 1 m below the at-rest sea surface at the time of image acquisition, or if the ratio $H/h \approx 1.02$.

A vortex street is observed (Figure 9a) downstream of a charted reef awash offshore of the port of Ras as Zwar (Figure 9b), located at 27° 56' 8" N, 49° 41' 4" E. The first shed vortex is approximately the characteristic diameter *L* downstream of the reef awash.

In the Lloyd and Stansby (1997 b) **awash** case, (or *H/h* value of 1.02) modeled oscillation of the wake begins down-current of the obstruction (Figure 9d) and distance between least depth of the obstruction and onset of the first shed vortex is approximately equal to the cross-current diameter *L.* Again, this real-life example has fit well with modeled awash submergence wake cases and is sufficient to confirm that the reef is properly positioned and represented on the ENC.

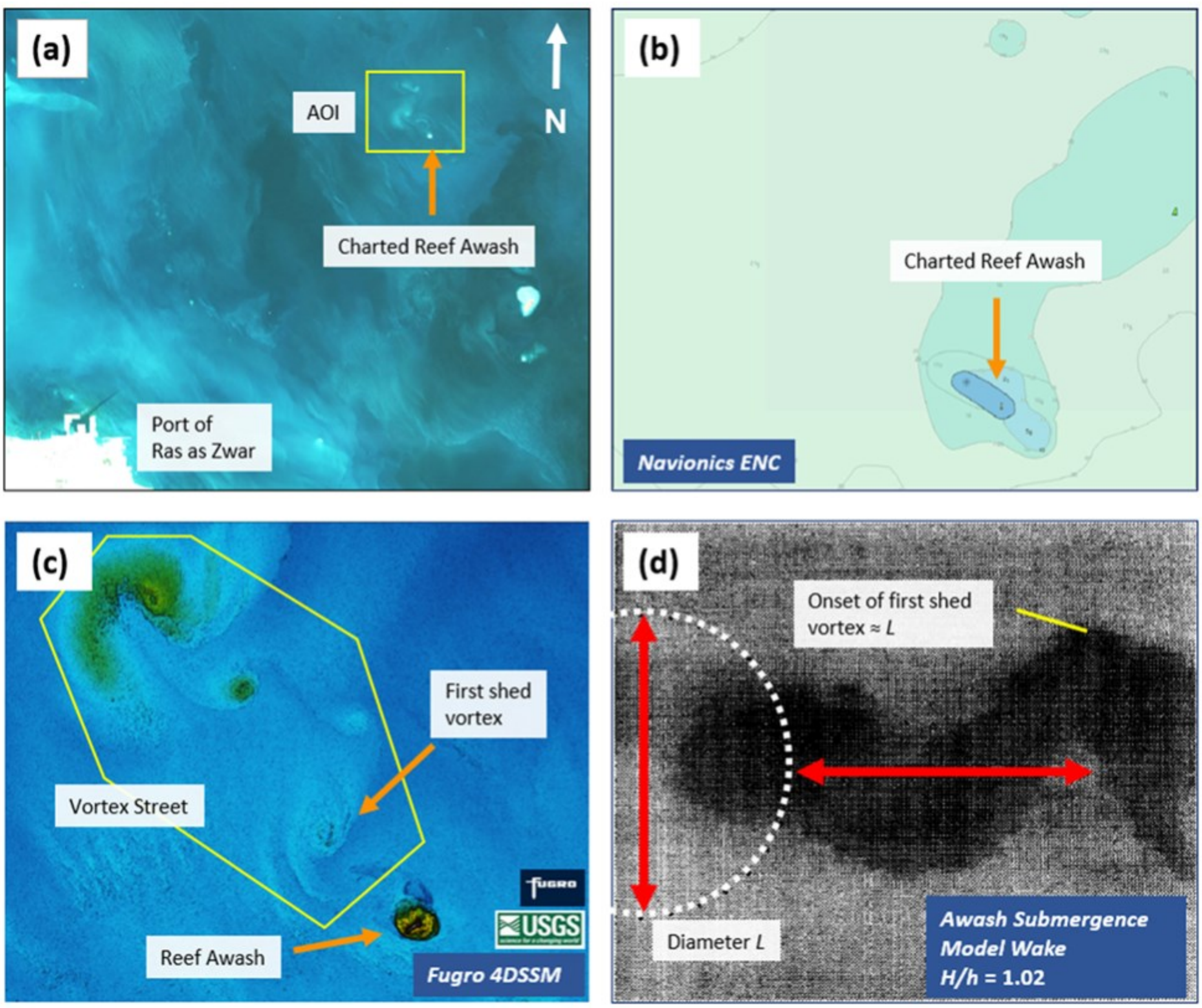


Figure 9: *(a) Landsat-8 image of Ras as Zwar and environs, showing the relative position of the reef. (b) Navionics ENC confirming that the least depth of the reef is awash. (c) Fugro 4DSSM scene of the reef and vortex wake. (d) Lloyd and Stansby (1997 b) model wake of awash submergence feature where diameter L is equal to the distance of the first shed of the vortex street from the maximum extent of the feature, as shown by the white dashed circle.*

Mid-Submergence Pattern

In the area of Ra’s Tanaqib, Saudi Arabia (see ***Figure 3*** for location), a charted coral head located at 28° 7' 21" N, 49° 10' 13" E (Figure 10a) has a least depth of 3m in depths of about 21 m (***Figure 10b***). A 4DSSM image of the area (***Figure 10c***) shows that the vortex morphology at this shoaling feature is defined by an oscillating wake down-current of the coral head before the first shed of the vortex street.

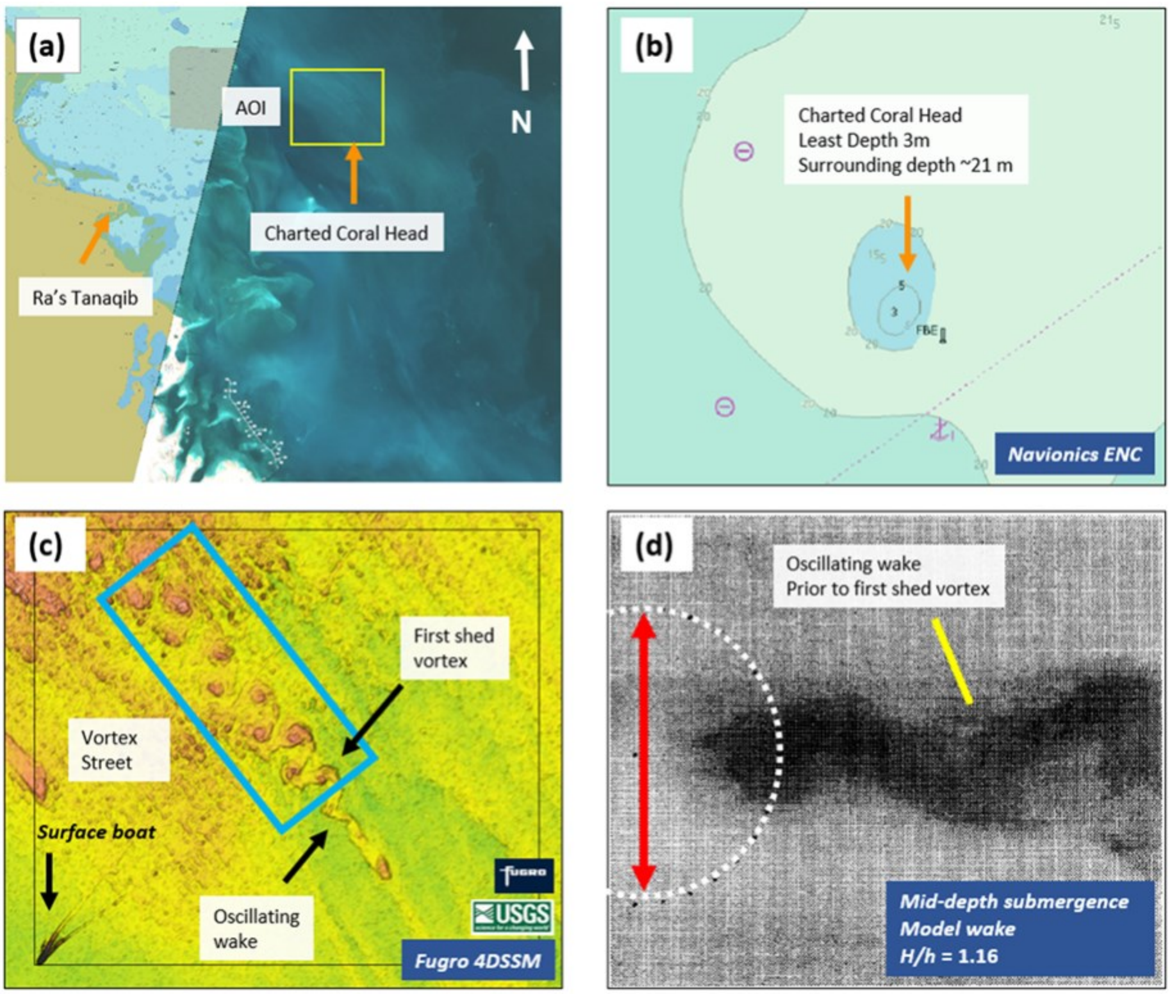


Figure 10: *Wake structure comparison for a charted coral head east of Ra’s Tanaqib, Saudi Arabia. (a) Landsat-8 image of Ra’s Tanaqib and environs, showing the relative position of the coral head. (b) Navionics ENC showing the charted least depth of 3 m and the surrounding depth of about 21 m. The coral head is marked with a buoy. (c) Fugro 4DSSM showing oscillating wake, first shed vortex, and oscillating wake. Note the surface vessel in the lower left-hand corner. (d) Lloyd and Stansby (1997) model wake for mid-depth submergence.*

This agrees well with the modeled Lloyd and Stansby (1997 b) **mid-depth submergence** case (submergence ratios 1.10 < H/h < 1.16), which also shows an oscillating wake prior to vortex formation. If a wake of this type is observed in satellite imagery in a location where an obstruction is not charted, the hydrographer can report the that a shallowly submerged feature is probable at that location.

Deep Submergence Pattern

An vortex street typical of deep submergence was observed on a seabed feature just outside an uncharted area east of Ra's Tanaqib at 27° 56' 15" N, 49° 17' 25" E (***Figure 11***). The area of interest in the Landsat-8 image (***Figure 11a***) corresponds to a navigational danger shown on the ENC as a navigational obstruction reported in 2003, least depth unknown (***Figure 11b***). Water depths in nearby areas with prior surveys are reported to be on the order of 15-18 m.

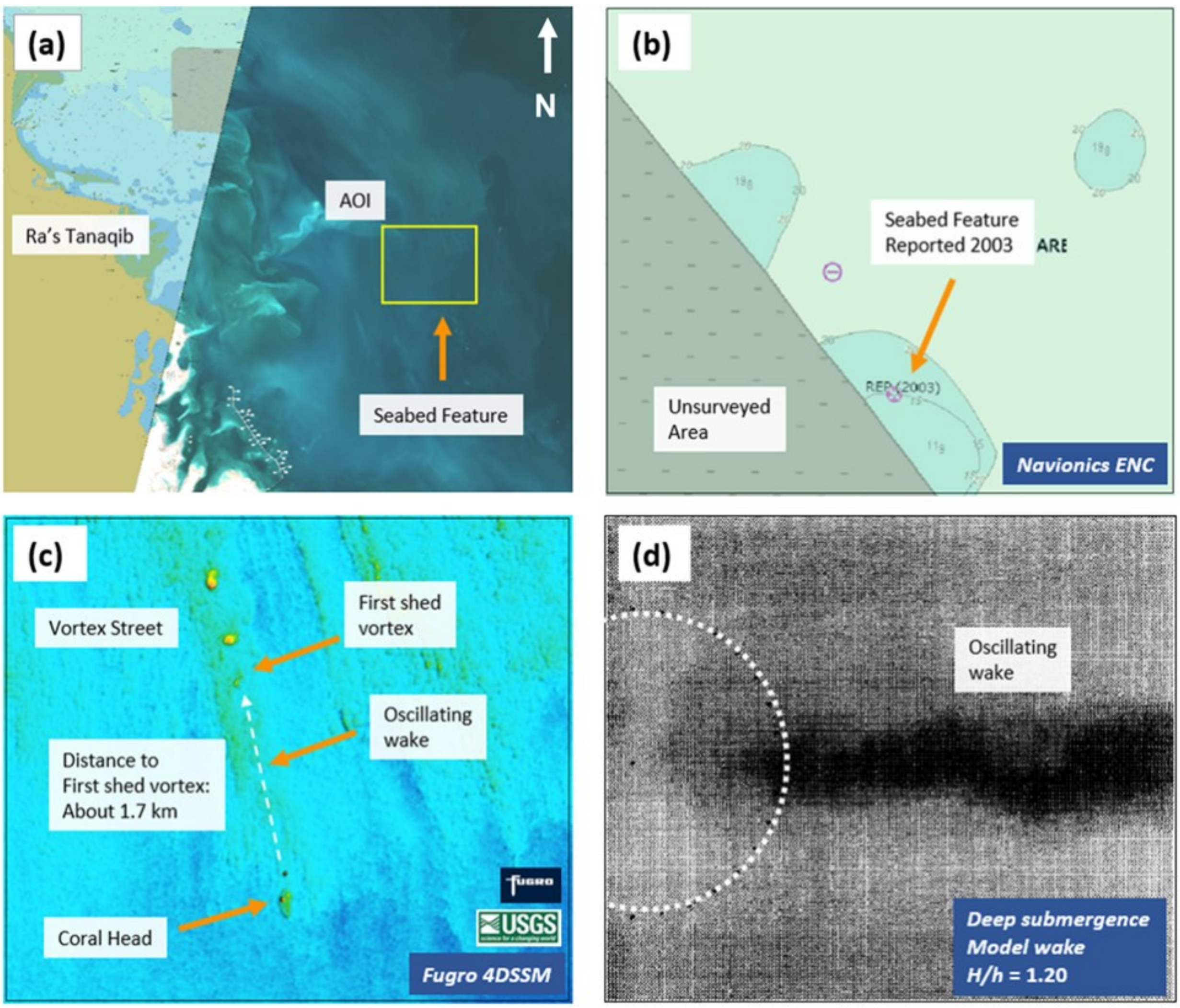


Figure 11: *Wake structure comparison for a charted Hazard Rep 2003 east of Ra's Tanaqib, Saudi Arabia. (a) Landsat-8 image of the area of interest and surrounding environs. (b) Navionics ENC of the feature, showing status as "reported" but no least depth. (c) Fugro 4DSSM scene showing coral head and two pinnacles with oscillating wake and vortex shedding down current. (d) Lloyd and Stansby (1997a b) model wake for deep submergence, for comparison with submerged pinnacles in (c).*

The Fugro 4DSSM scene of the feature shows a distinct coral head (***Figure 11c***) with a trailing vortex wake where onset of vortex shedding is 1.7 km downstream. In the **deep submergence case model** (submergence ratios 1.16 < H/h <1.20), water preferentially flows over the top of the obstruction rather than separating horizontally, suppressing the onset of vortex shedding. A narrow oscillating wake forms behind the obstruction and gradually changes to a weak vortex street (Lloyd and Stansby, 1997 b).

Using Vortex Street Morphology in Hydrographic Survey Practice

The existence of a vortex street seen in the water column of satellite imagery is sufficient to demonstrate that a seabed object is real, and the shape of the vortex street allows the hydrographer to quickly estimate relative least depth. Together, these are useful tools for assessing the survey area for hazards and to check chart accuracy and adequacy.

In the vicinity of the port of Ras as Zwar are two examples of how to apply this information. ***Figure 12*** shows the general location of two inadequately charted hazards relative to the port.

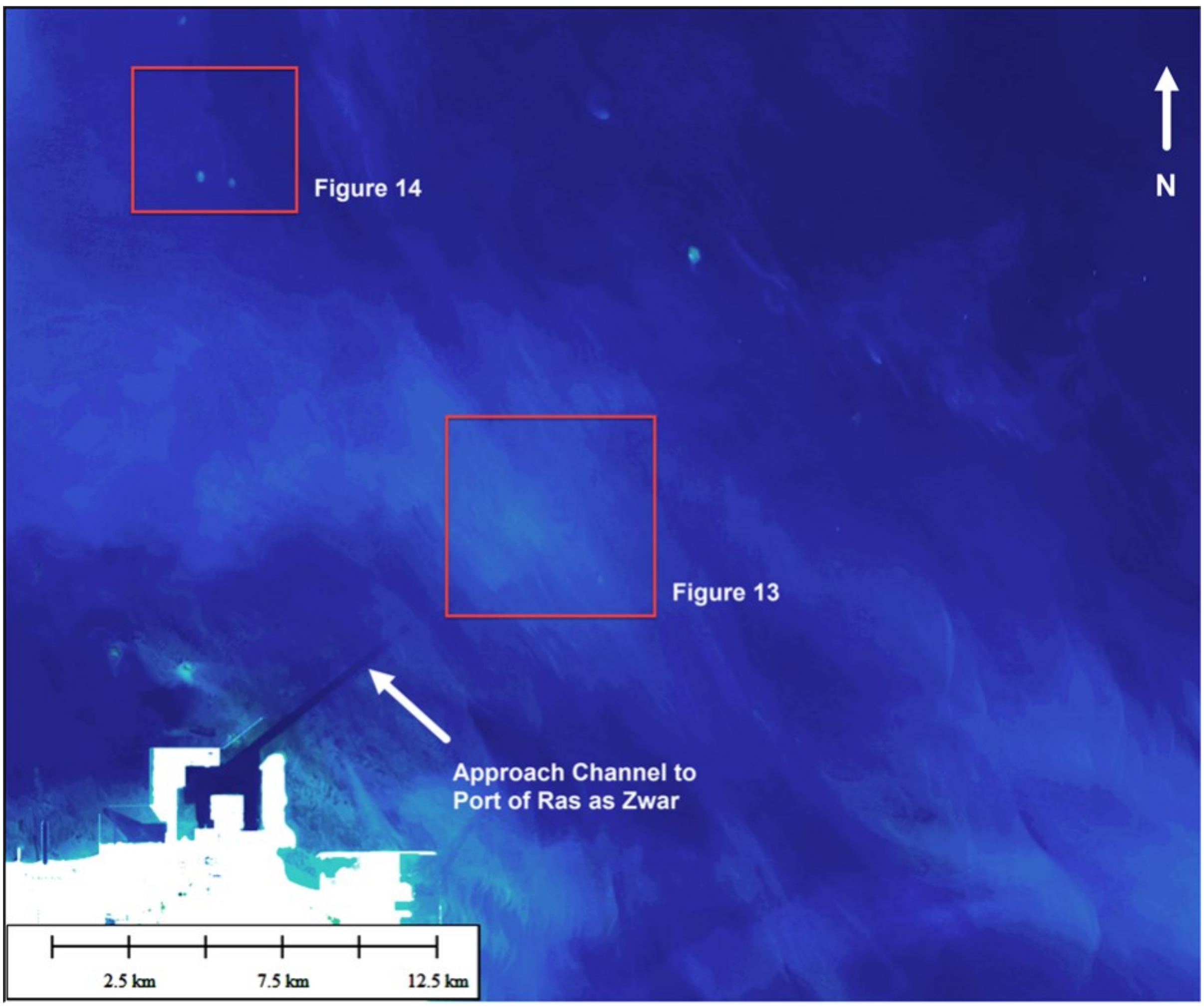


Figure 12: *Approaches to Port of Ras as Zwar. Red boxes denote inadequately charted objects with vortex streets.*

In ***Figure 13***, a vortex street is observed flowing downstream of a coral head near the entrance channel to the port of Ras as Zwar, at 27° 37' 22" N, 49° 19' 28" E. The shape of the vortex street (Figure 13a) closely resembles an awash or shallowly-submerged object with submergence $1.02 < H/h < 1.05$ as per Lloyd and Stansby (1997 b). The charted least depth at the position of this coral head is 4.9 m in surrounding depths of about 10-12 m (Figure 13b), which gives a submergence value $H/h = 2.04$, which is too large a submergence value for a vortex street to form at all.

Green arrows in Figure 13 (a-b) point to the position of a charted rock awash. No vortex street is observed downstream of this charted rock. It is unknown if other physical factors prohibiting vortex street formation are present (vortex streets are sufficient for hazard identification, but not necessary). This charted rock awash is approximately 3.2 km east of the uncharted dangerous rock identified by the vortex street. It is unknown if the charted rock awash is incorrectly positioned on the ENC or if two rocks exist.

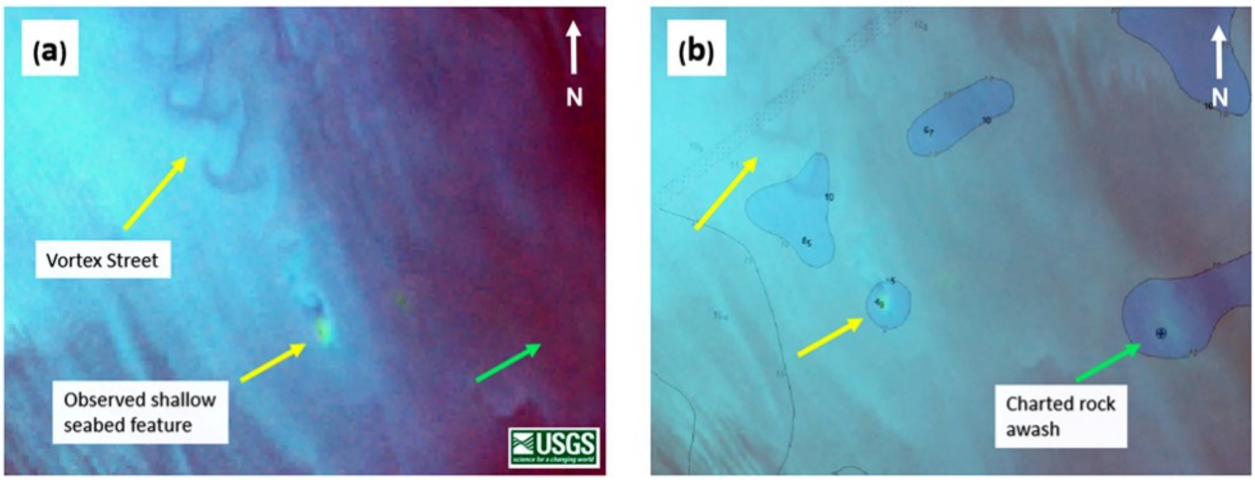


Figure 13: *(a) Landsat-8 image showing vortex development indicative of a shallow submerged feature (indicated by yellow arrows). (b) Nautical chart superimposed on satellite image showing a charted rock awash (black arrows). Note the location of the vortex in (a) does not align with the charted feature.*

The presence of the vortex street is sufficient to conclude that a real feature exists at that point, that the charted least depth at that position is incorrect, and to flag the both the newly found rock and existing charted rock as requiring further surveying. A prudent hydrographer may use this information to issue a Notice to Mariners warning of a dangerous rock with least depth unknown to ensure that mariners approaching the Ras as Zwar channel can give the hazard wide clearance. This information is also suitable for survey planning, particularly in planning safe operations around a dangerous rock of unknown depth for a vessel-based survey.

A second example of using vortex wakes to resolve low-certainty position and depth is shown in ***Figure 14***. A pair of charted coral heads with turbulent wakes, located at 27° 44'2 1" N, 49° 11' 30" E, are shown in a Landsat-8 imagery (Figure 14a) and the Navionics ENC for the area (***Figure 14b***). The western coral head has a vortex street wake that suggests that the coral head is awash or drying at low water. The eastern coral head has an oscillating bubble wake that dissipates as it encounters the vortex street.

Satellite imagery overlaid on the nautical chart shows that the distance as measured from the center of the western coral head to the center of the charted low-water area is greater than 660 m. For immediate safety to navigation, the position of the coral head can be sent out via Notice to Mariners as a dangerous rock, least depth unknown. This position can later be quantitatively updated to International Hydrographic Organization (IHO)-compliant position and least-depth accuracies using SDB or *in-situ* surveying.

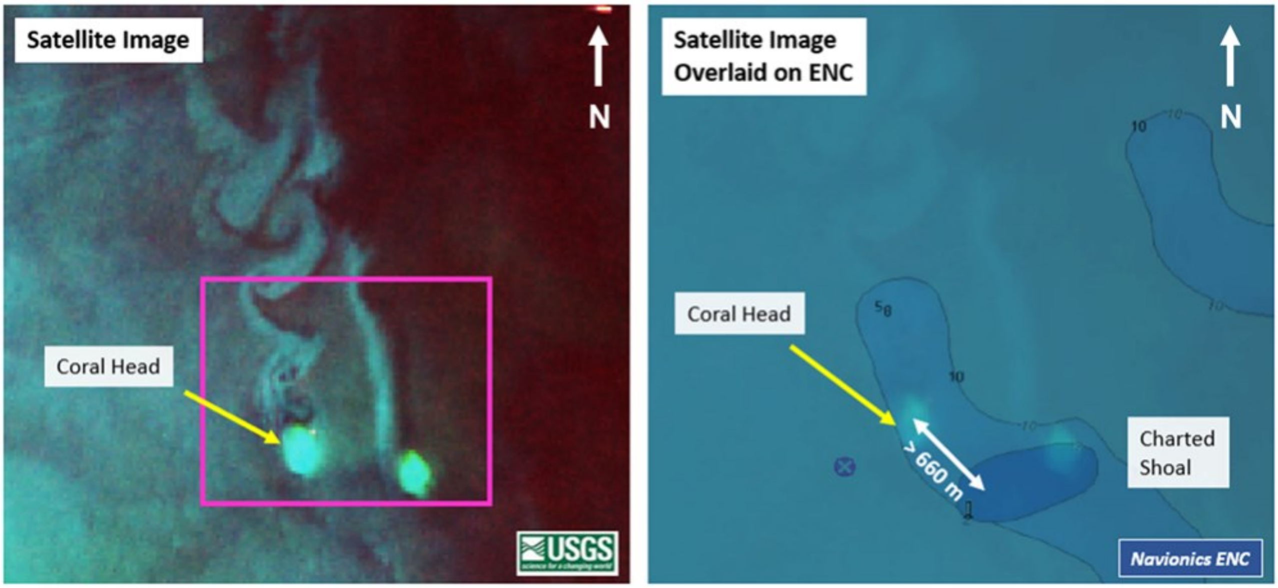


Figure 14: *(a) Satellite image showing vortex development at coral head. (b) Image laid over Navionics ENC showing incorrectly charted positions and least depths.*

Variation in the presence and shape of vortex streets at different stages of tide is visible in imagery of the charted hulk in Ad Dammam first described in ***Figure 5***. The shape of the wake behind the exposed hulk varies according to phase of tide (***Figure 15 a-d)*** and illustrates the need to investigate satellite images acquired at several points through a tidal cycle. Although the superstructure and masts of the wreck are surface piercing at all phases of tide, the shape of the wake in ***Figure 14 (b)*** suggests that the main deck of the wreck is awash or shallowly submerged. Curiously, vortex streets were not observed in any images acquired during periods of rising tide, although the ephemeral relict vortices of a vortex street formed during a falling tide are visible in an image acquired one hour after low tide (***Figure 15d***). These relict vortices are interpreted to have sufficient residual rotational energy to persist in despite the change in tidal stream magnitude and direction.

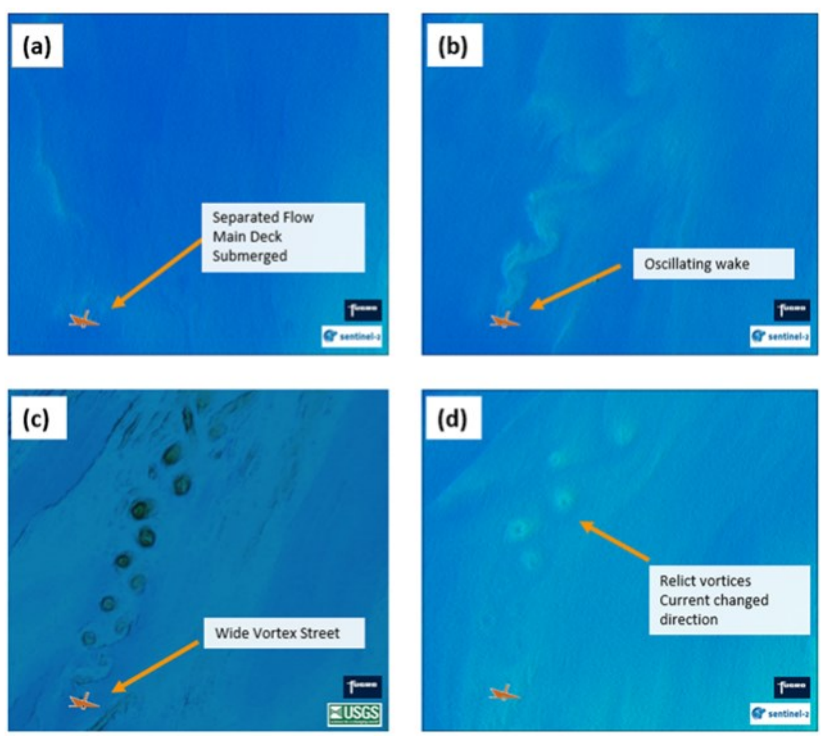


Figure 15: *Satellite images charted a dangerous wreck (orange exposed wreck symbol), through tidal phases. (a) High tide (b) half-way between high and low tide with oscillating wake, (c) low tide with vortex street, (d) one hour after low tide showing no wake but relict vortices.*

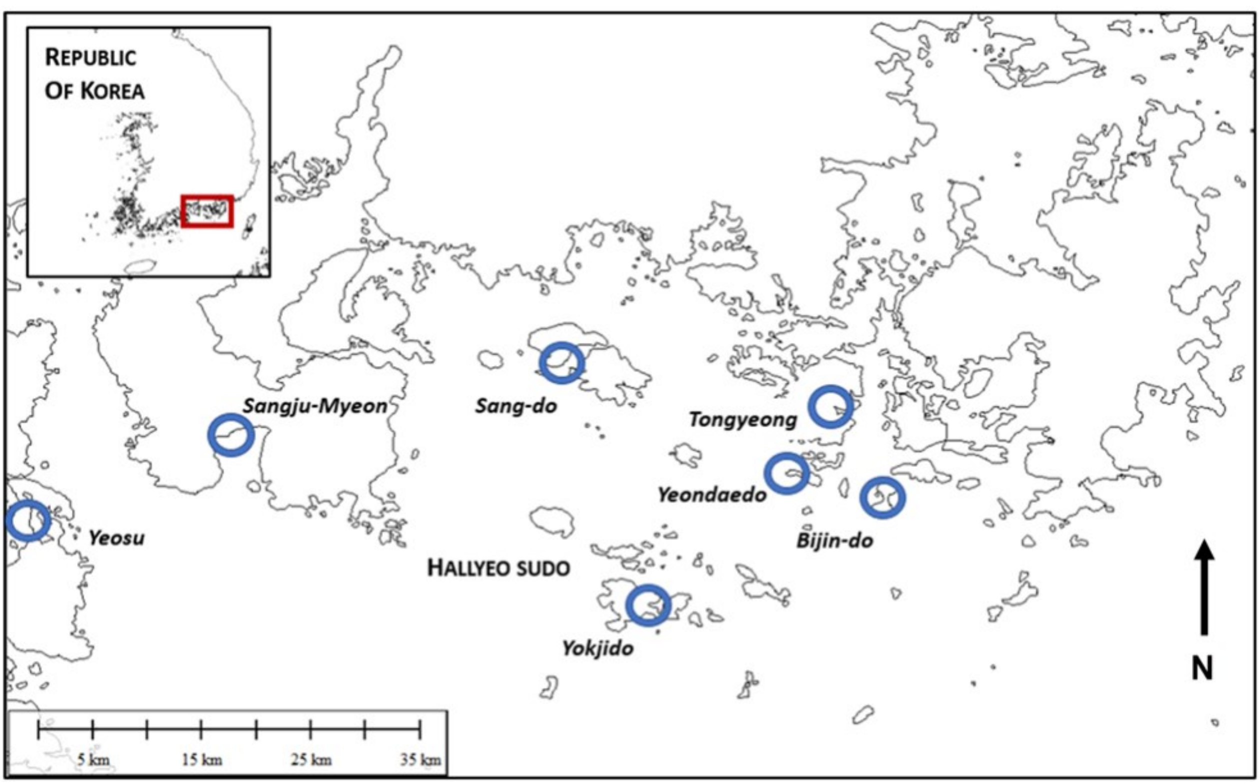
Case Study 2: Vortex Dipoles, Hallyeo Sudo, Republic of Korea

Study Area Background

The Hallyeo Sudo waterway is an open bay between the Goseong Peninsula and the Yeosu Peninsula, on the east side of the Korea Strait in the Republic of Korea (***Figure 16***). The ports of Tongyeong, Yeosu, Geoje, and Sacheon are located on islands and peninsulas surrounding the embayment. Coves and small basins around the individual islands are home to aquaculture rafts growing oysters for consumption and for pearl production. The islands and islets vary in cross-current diameter from islets 50 m in diameter to inhabited islands more than 4 km wide, with clusters of islands separated by shallow channels less than 15 m deep. Charted water depths in open-water areas vary from 60 – 200 m.

Local sea conditions in the Hallyeo Sudo area are influenced by the presence of the East Korea Warm Current, a branch of the Kuroshio Current. With this close proximity to a fast-flowing western boundary current, Hallyeo Sudo waters are typically warm (on the order of 25 °C) and turbid with strong currents and seasonally variable salinity as Yellow Sea and East China Sea waters are entrained into the flow (Park et al, 1999). Although currents are not uniform in strength or direction across the study area, current velocities in Hallyeo Sudo are uniformly strong enough to support vortex formation.

Figure 16: *Case Study 2 – study area in Hallyeo Sudo, Republic of Korea. Map outlines from World Maritime Boundaries v.11.*

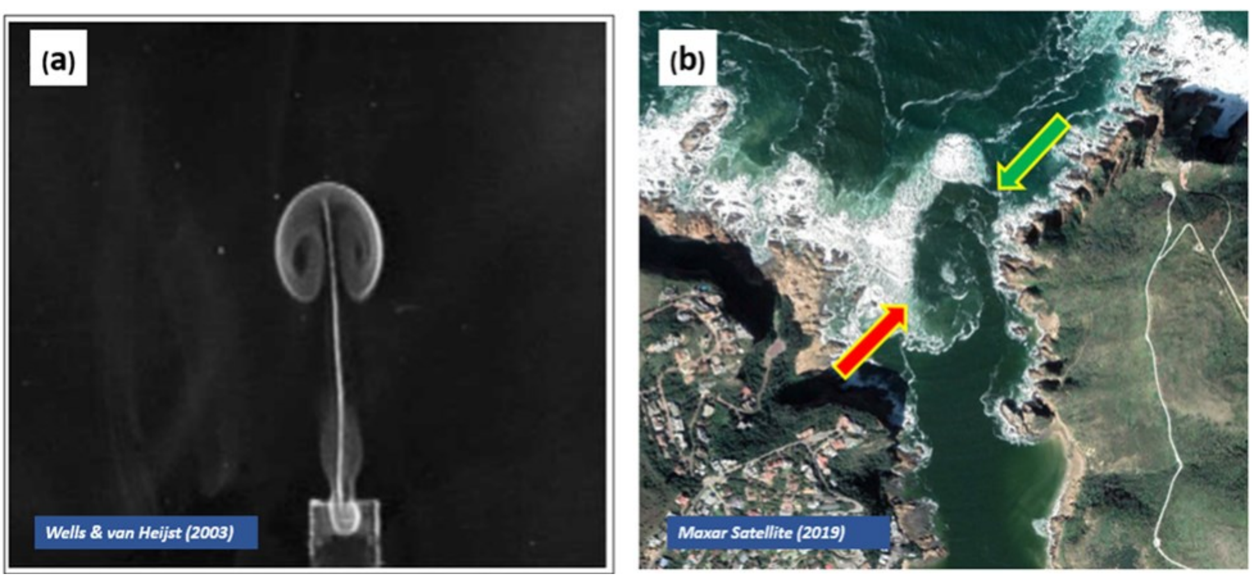


Vortex Dipoles

When a strong, near-coastal current flows from a topographically constrained environment to an open-water, lower-current environment, such as between an island gap or around the tip of a headland, viscous boundary layers form between the jet current and the surrounding bedforms causing high-vorticity shear layers to develop in the jet. When the high-vorticity jet current emerges from the channel into a low-vorticity basin, paired counter-rotating vortices develop. These paired vortices are referred to as a vortex dipole.

The classic presentation of a vortex dipole resembles a mushroom shape where a line drawn between the centers of counter-rotating axisymmetric vortices is normal to the direction of the jet (***Figure 17a***). The appearance of dipoles in coastal oceans varies due to mechanism of formation (gap-forming or headland-forming), the shape of the seabed channel, phase of tide, and prevailing currents (Kashiwai, 1985). Both classically-appearing axisymmetric vortex dipoles and asymmetric vortex dipoles appear in nature (***Figure 17b***) and the presence of any observed dipoles should be considered during hydrographic analysis of an area.

Figure 17: *(a) Test tank vortex dipole showing classic mushroom shape, adapted from Wells & van Heijst (2003) and (b) asymmetric gap-forming vortex dipole at Knysna Head, Western Cape, South Africa (Maxar Worldview 4 Satellite). The red and green arrows point to the centers of each vortex of the dipole.*



Vortex dipoles in navigable coastal waters are classified into two types: headland-forming and gap-forming. Headland-forming vortex dipoles will form as a jet current flows past the tip of an island, headland, or similar non-surface-piercing seabed feature when bottom drag is low relative to size of the headland and tidal excursion (Signell and Geyer, 1991). These dipoles may be preceded by monopoles (single vortex) adjacent to the stronger dipole vortex. Gap-forming dipoles develop when a sufficiently strong current passes through a narrow channel between islands or a cut in a headland. Gap-forming vortex dipoles are influenced by changes in current speed and direction at the gap caused by change in tidal streams. Both headland-forming and gap-forming vortex dipoles observed in coastal waters are three-dimensional: the seabed itself is three-dimensional, as is current flow, and thus the boundary layers that form between jet current and bedforms must also be three-dimensional.

Vortex dipoles do not grow indefinitely. Gharib et al (1998) observed that for a closed channel in a laboratory with current speed U and propagation time t divided by island gap width W in a channel of constant diameter, when the value of the dimensionless ratio

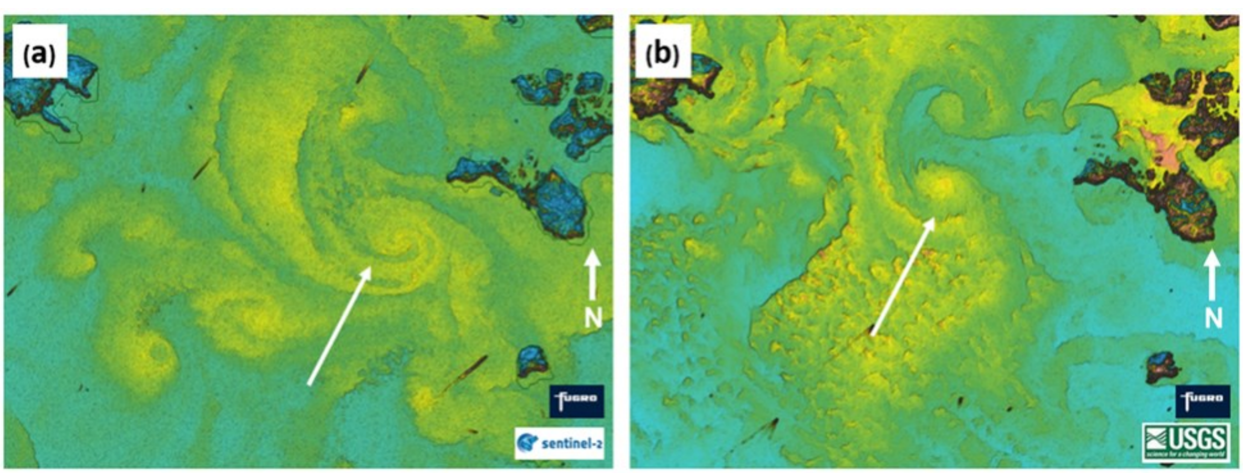
Equation 3.

$$\frac{U\,t}{W} \approx 4,$$

the paired vortices will separate from the jet in a process known as pinch-off. Pinched-off vortices observed in satellite imagery indicate that the jet current creating the dipoles is sufficiently strong to induce visible vorticity, even if (as is typical in tidal streams) the absolute magnitude of jet current speed varies over time. Pinched-off vortices become entrained in the prevailing currents of the low-vorticity basin.

Examples of headland-forming vortex dipole are observed west of Yeondaedo Island at approximate position 34° 44' 00" N, 128° 22' 00" E. The forward edge of the dipole was detected in a similar location in two Fugro 4DSSM scenes (***Figure 18***), however the size and symmetry of the dipole varies suggesting variability in the flow regime at the time each image was taken. For instance, on an image taken in January (***Figure 18a***) an asymmetric dipole form with stronger rotation in the more southerly vortex as the tidal stream passes south of the island (white arrow; ***Figure 18a***). The appearance of an asymmetric dipole with stronger rotation in one of the two vortices is consistent with Signell and Geyer's (1991) model where vortex growth is encouraged on one side due to low bottom drag relative to size of the headland, but vortex growth was inhibited on the other side of the headland where bottom drag was high. At a different time of year in the same area, an image taken in October (***Figure 18b***), shows that even though the **shape** of the dipole is more symmetric, the **intensity** of the vortex dipole is asymmetric due to drag around the headland. (Note: intensity, in this case, is interpreted by the stronger reflectivity (brighter colors) which indicates more suspended material in the water column, which in turn implies more intense rotation.)

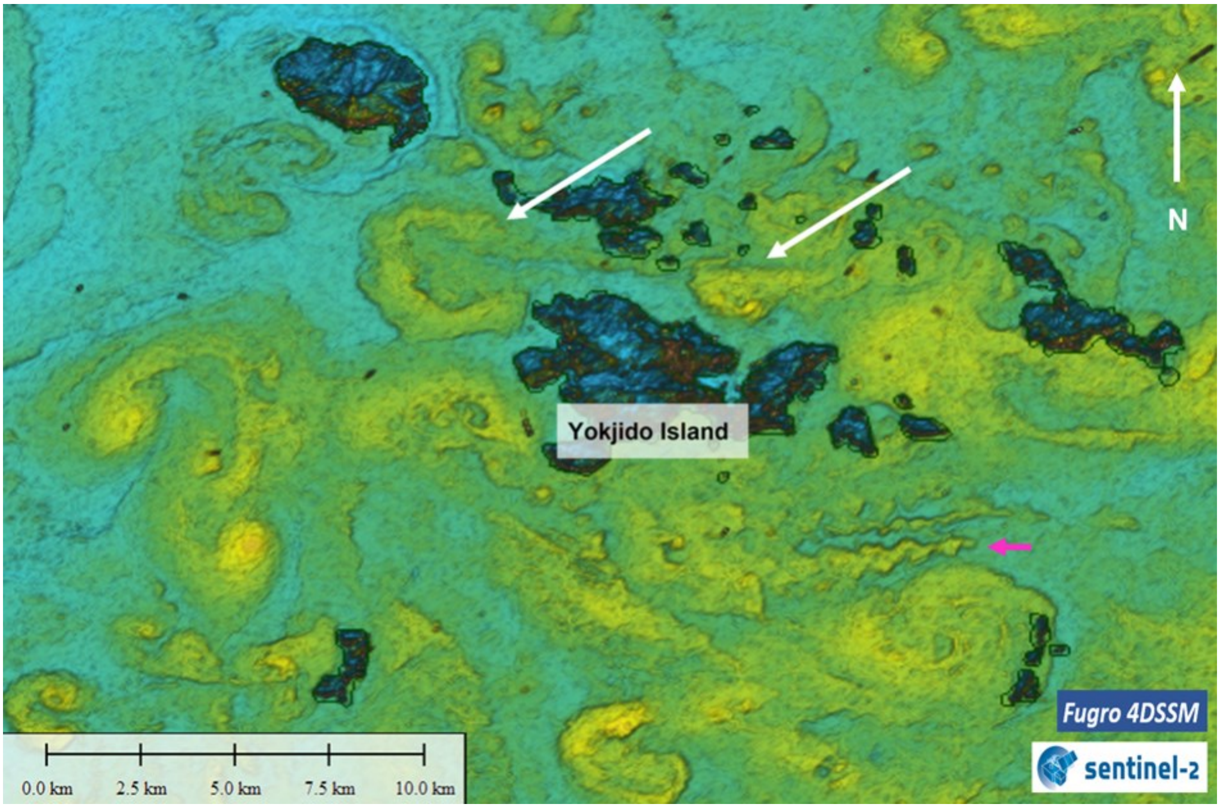
Figure 18: *Headland-forming dipoles near Yeondaedo Island in Fugro 4DSSM Scenes. (a) Sentinel-2 from 15 January 2020 showing asymmetric dipole vortices developed around a headland. (b) Landsat-8 from 31 October 2017 in the same area where the dipole has a more symmetric shape. White arrows in each image point to the dipole vortex with the more intense rotation.*



Examples of gap-forming vortex dipoles are observed immediately north of Yokjido Island at approximate position 34° 39' 45" N, 128° 12' 20" E. A large dipole is present to west of the channel between Yokjido Island and Hanodaedo Island, and a smaller dipole is present between two islands to north and east of Yokjido island (***Figure 18***).

Figure 19: *Gap-forming dipoles (white arrows) near Yokjido Island, Republic of Korea, in a Fugro 4DSSM scene based on a Sentinel-2 image dated 20 January 2020. Magenta arrow indicates a trio of Von Kármán vortex streets.*

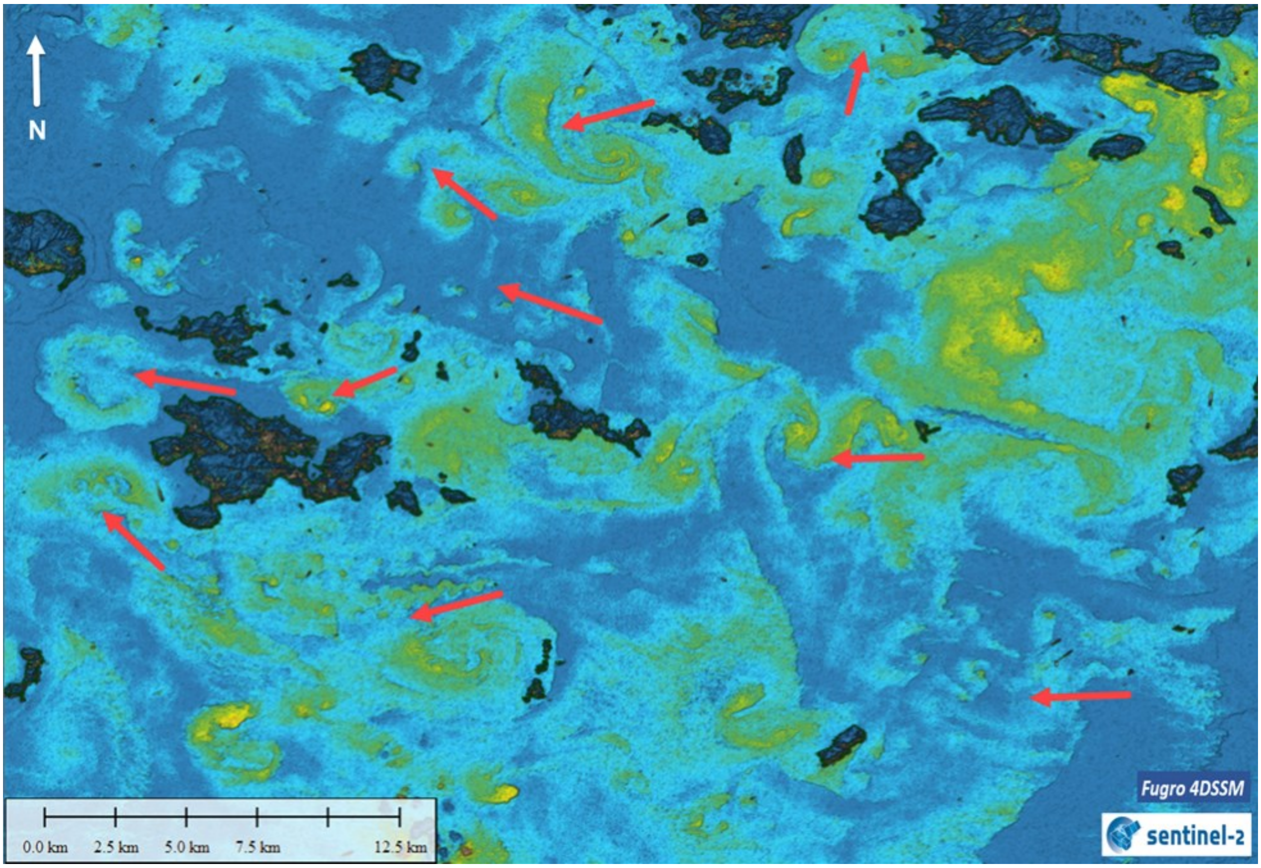
Using vortex dipoles in hydrographic survey planning



Surface currents interacting with the numerous islands of Hallyeo Sudo produce complex patterns of vortex generation. The presence of vortex dipoles is sufficient to anticipate strong currents in a hydrographic area of interest. Dipole position and orientation may be used as a proxy to estimate current speed and direction for the purposes of hydrographic survey planning. Assessing satellite imagery in this manner helps to more accurately assess operational survey needs as well as mitigating potential operational problems (such as an underpowered vessel or vehicle unable to hold line in swift currents).

In the east of the Hallyeo Sudo, complex vortex patterns may be used to interpret the direction of surface currents (***Figure 20***). Red arrows indicate interpreted surface currents in the frame. A surface vessel with a multibeam echosounder running lines oblique to or across the current is likely to crab, reducing swath width and thus reducing survey efficiency. Crab angles will also reduce the position quality of towed instruments that are positioned using layback methods. By observing the positions and direction-of-propagation of vortex dipoles in several images at different phases of tide, the hydrographer may plan a more efficient, cost-effective survey.

Figure 20: *Fugro 4DSSM scene of the Hallyeo Sudo near Bijin-Do Island, based on Sentinel-2 imagery from 20 January 2020. Red arrows indicate surface current directions as interpreted from visible vortex streets and vortex dipoles.*



5. Discussion

The use of water column data in optical-band satellite imagery as presented in the two case studies in this paper is novel in hydrography. There are many potential hydrographic survey uses for satellite water column data that are as yet unexplored, provided that hydrographers expand their criteria for adequate-quality satellite imagery beyond only those images that are adequate for SDB processing and seek potential uses of satellite imagery data beyond merely determining least depths for a chart.

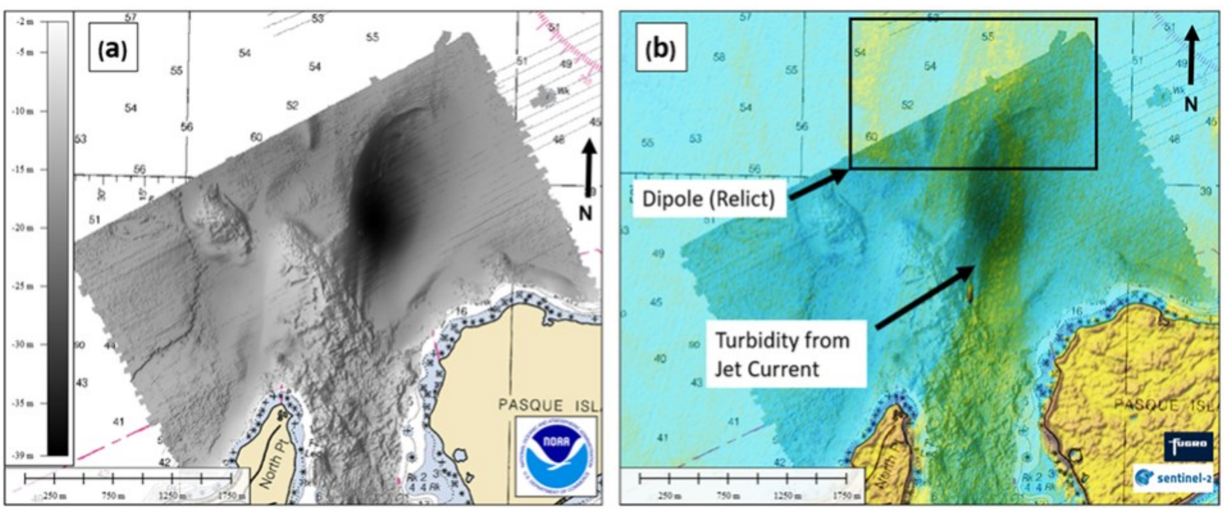
An acknowledged limitation of this study is that it is observational and qualitative, based on remotely sensed imagery that has not been ground-truthed. Additional *in-situ* research with ALB or MBES is required to validate the relationship between observed morphology of vortex streets in satellite imagery and estimated submergence of the source object, and also of course to determine adequate-quality tidally reduced least depths for charting.

If it is possible to modify existing SDB algorithms or to create novel algorithms to estimate least depths for seabed features based on morphology of vortex streets, this too is suggested as a venue for additional research.

Other research topics based on this novel use of satellite imagery require both analysis of the water column itself and *in-situ* surveys with MBES. In-water vortex features are three-dimensional and may extend from surface to seabed. How these features interact with seabed bedforms is not well understood.

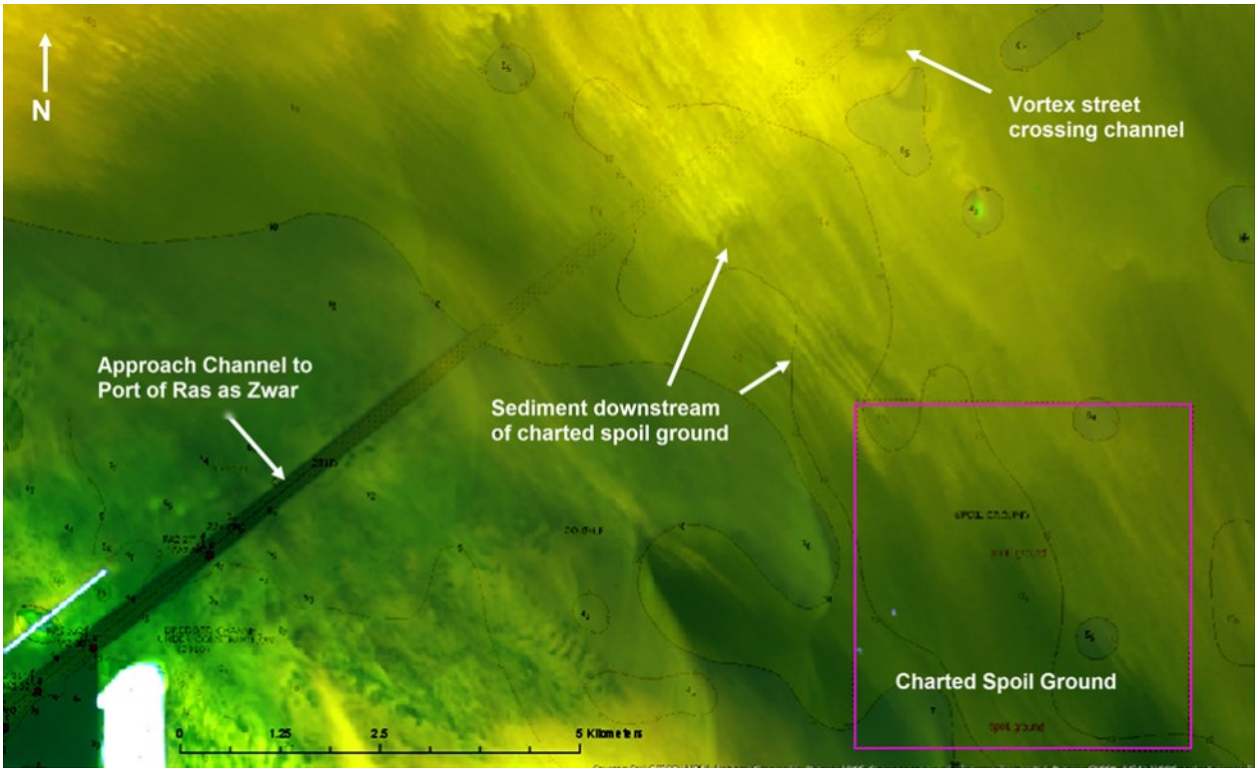
An example of where interaction between a vortex dipole and the seafloor may be studied is in Quicks Hole, Massachusetts, USA. Figure 20 (a) shows a MBES Digital Terrain Model conducted by a United States government vessel in 2004 overlaid on the corresponding NOAA raster nautical chart. In ***Figure 20 (b)***, a Fugro 4DSSM scene based on a Sentinel-2 image dated 16 March 2019 and overlaid on the NOAA bathymetry shows the presence of a vortex dipole whose maximum excursion corresponds to a large scour depression (black) in the MBES imagery. The trailing jet of the vortex dipole follows the shape of a subsea ridge observed in the MBES data. It is not known if the scour depression is a consequence of vortex dipole activity or if the collocated presence of dipole and depression is merely coincidental. Conducting additional surveys of the area with MBES water column and vessel-mounted Acoustic Doppler Current Profiler (ADCP) will shed light on this question.

Figure 21: *(a). NOAA 2004 MBES survey, overlaid on NOAA chart 13229. (b) Fugro 4DSSM scene based on Sentinel-2 image dated 15 January 2019. The trailing jet and vortex dipole follow the seafloor morphology and terminate over the large seafloor depression. This image was acquired approximately 1 hour after low water, so both the vortex dipole and turbidity from the jet current are considered as relict.*



Vorticity in the water column is not the only water column data available in satellite imagery. As demonstrated by the work of Soares et al (2019) described in the Introduction to this paper, satellite imagery can be used to determine suspended sediment load. ***Figure 21***, located in the Arabian Gulf AOI, shows the Navionics ENC of the area overlaid on false-colour imagery from the same Landsat-8 image as the case study. Suspended sediment downstream of a charted spoil ground and in the vortex street on the dangerous rock cross the dredged channel leading to the port of Ras al Khas Zwar. Combining periodic *in-situ* surveys of the spoil area and channel by MBES with concurrent analyses of suspended sediment load from optical-band satellite imagery is suggested to determine whether we can predict rate of shoaling or need for dredging based on time-series studies of satellite imagery.

Figure 22: *Approach channel to Ras as Zwar, Kingdom of Saudi Arabia, with turbid features and charted spoil ground highlighted.*



6. Conclusions

Optical-band satellite images excluded from SDB processing due to vortex-induced turbidity have value and can add a new and useful tool into the hydrographer's toolbox.

The authors suggest that hydrographers need not wait for further research on computational methods and may immediately begin to use imagery from available public and private satellites to review existing charts for accuracy, issue Notices to Mariners or chart updates based on findings, and plan new surveys. As computational methods become available, these too may enter the hydrographer's toolbox.

Water column turbidity created by vortex streets and vortex dipoles that are visible in satellite imagery provides useful information about seabed morphology and water column properties such as:

- Uncharted hazards
- Depth of submerged hazards
- Local current directions
- Local current relative velocities

For best results, multiple satellite images, or time series, of the same area should be analyzed during different phases of tide, lunar months, or seasons in order to:

- Understand the hydrodynamic environment in an area

- Understanding the survey area environment as a whole, which may help with choices of equipment, line planning, and survey time constraints
- Assess chart quality for submerged hazards.

Hydrographers are encouraged to review images for vortex features and to analyze the features they find. Products may be derived from direct observation, computations, or future developments of satellite image products.

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8. Authors Biography

Helen Stewart is an NSPS/THSOA Certified Hydrographer employed by Fugro in Houston, USA. In her broad and diverse career, Helen has worked in many different aspects of hydrography, from charting, geophysical, and deepwater AUV projects to marine construction and oceanographic research. She has a Master of Science from the University of Cape Town and a Bachelor of Science from the University of Texas at Austin. E-mail: hstewart@fugro.com

Robert van de Poll is the Global Director for Law of the Sea (LOS) at Fugro. In 1998, at the request of the United Nations, Robert developed a software suite of customized GIS tools to address all offshore Law of the Sea applications as defined in the United Nations Global UNCLOS Treaty. Robert designed, created and developed the LOS-GIS Product CARIS-LOTS. He worked at CARIS for 15 years (1991 - 2006Robert has now completed over 1800 Law of the Sea specific projects in 142 countries since joining Fugro in 2006. E-mail: rvdpoll@fugro.com

Kelley Brumley is a marine geologist and is an adjunct professor at University of Houston and Affiliate Faculty at University of Alaska Fairbanks (UAF), and a private consultant and broker on seafloor mapping projects. She received an M.S. in geology from UAF and a Ph.D. from Stanford University. Between 2006-2012, she was a member of the science party during the U.S. and Canada’s Extended Continental Shelf mapping efforts in the Arctic Ocean. Dr. Brumley has acted as lead scientist on many regional multibeam mapping and geochemical coring surveys investigating cold seep locations and related chemosynthetic habitats. E-mail: kbrumley@marietharp.org

Articles

THE BALTIC SEA CHART DATUM 2000 (BSCD2000)

Implementation of a common reference level in the Baltic Sea

By J. Schwabe [1], J. Ågren [2], G. Liebsch [1], *P. Westfeld [3], T. Hammarklint [4], J. Mononen [5] and O. B. Andersen [6]*

1. Federal Agency for Cartography and Geodesy (Germany)
2. University of Gävle (Sweden) and Lantmäteriet, the Swedish mapping, cadastral and land registration authority (Sweden)
3. Federal Maritime and Hydrographic Agency (Germany)
4. Swedish Maritime Administration (Sweden)
5. Finnish Transport Agency (Finland)
6. DTU Space (Denmark)

Abstract

The *Baltic Sea Chart Datum 2000* (BSCD2000) is a geodetic reference system adopted for Baltic Sea hydrographic surveying, hydrographic engineering, nautical charts, navigational publications and water level information. It is based on the common geodetic standards for the height system (EVRS) and the spatial reference system (ETRS89) in Europe. In particular, the zero level of BSCD2000 is in accordance with the Normaal Amsterdams Peil (NAP). BSCD2000 is about to be adopted as unified chart datum by all the countries around the Baltic Sea. It agrees with most national height realizations used on land. BSCD2000 will facilitate effective use of GNSS methods like GPS, GLONASS and Galileo for accurate navigation and hydrographic surveying in the future.

Résumé

Le *Baltic Sea Chart Datum 2000* (BSCD2000) est un système de référence géodésique adopté pour les levés hydrographiques, l'ingénierie hydrographique, les cartes marines, les publications nautiques et les informations sur le niveau de l'eau de la mer Baltique. Il est basé sur les normes géodésiques communes au Système de Référence Vertical Européen (EVRS) et au Système de Référence Terrestre Européen (ETRS89). En particulier, le zéro hydrographique du BSCD2000 est conforme au *Normaal Amsterdams Peil* (NAP). Le BSCD2000 est sur le point d'être adopté en tant que niveau de référence des cartes commun par l'ensemble des pays bordant la mer Baltique. Il correspond à la plupart des mesures de hauteur nationales utilisées à terre. Le BSCD2000 facilitera l'utilisation efficace des méthodes du GNSS comme le GPS, GLONASS et Galileo pour une navigation et des levés hydrographiques précis à l'avenir.

Articles

Resumen

El *Dátum 2000 de la Carta del Mar Báltico* (BSCD2000) es un sistema de referencia geodésico adoptado para los levantamientos hidrográficos del Mar Báltico, la ingeniería hidrográfica, las cartas náuticas, las publicaciones náuticas y la información sobre el nivel del mar. Se basa en las normas geodésicas comunes para el sistema de alturas (EVRS) y en el sistema de referencias espaciales (ETRS89) en Europa. En particular, el nivel cero del BSCD2000 está en consonancia con el *Normaal Amsterdams Peil* (NAP). El BSCD2000 está a punto de ser adoptado como datum de cartas unificado por todos los países que rodean el Mar Báltico. Concuerda con la mayoría de las realizaciones de alturas nacionales utilizadas en tierra. El BSCD2000 facilitará el uso efectivo de los métodos GNSS como el GPS, GLONASS y Galileo para la navegación precisa y los levantamientos hidrográficos en el futuro.

1. Motivation

The Baltic Sea is an international shallow, non-tidal area in the northern part of Europe with dense traffic. Accurate depth data and water level information is of absolute importance to preserve the safety of navigation in the area. So far, numerous local reference levels were used in the Baltic Sea for nautical charts and water level information, such as water level observations, forecasts and warnings. The exact definition of the chart datum may vary between countries, regions as well as over time. The matter of these existing Baltic Sea chart datums is a rather complex issue, not only for the navigators, but also for the responsible hydrographic offices and other users of depth data in general. Thus, a unified vertical reference system is important to improve navigation in the Baltic Sea region.

For centuries, the chart datums in the Baltic Sea were defined as the “mean sea level” (MSL), which was observed at tide gauges, i.e., a height obtained by a long-term average of the sea level readings measured with respect to the land at the particular tide gauge location. This implies that the chart datum is influenced by two different quantities – long term sea level changes as well as possible height changes of the land. Both quantities could not be observed separately. This has a great impact especially in the Baltic Sea region which is strongly affected by the postglacial Scandinavian land uplift phenomenon. While the climate-induced sea level rise has an order a few millimeter per year, the land uplift affects the heights by up to one centimeter per year. This results in a lowering of the depth in major areas of the Baltic Sea and is well observable by mareographs (see ***Figure 1).***

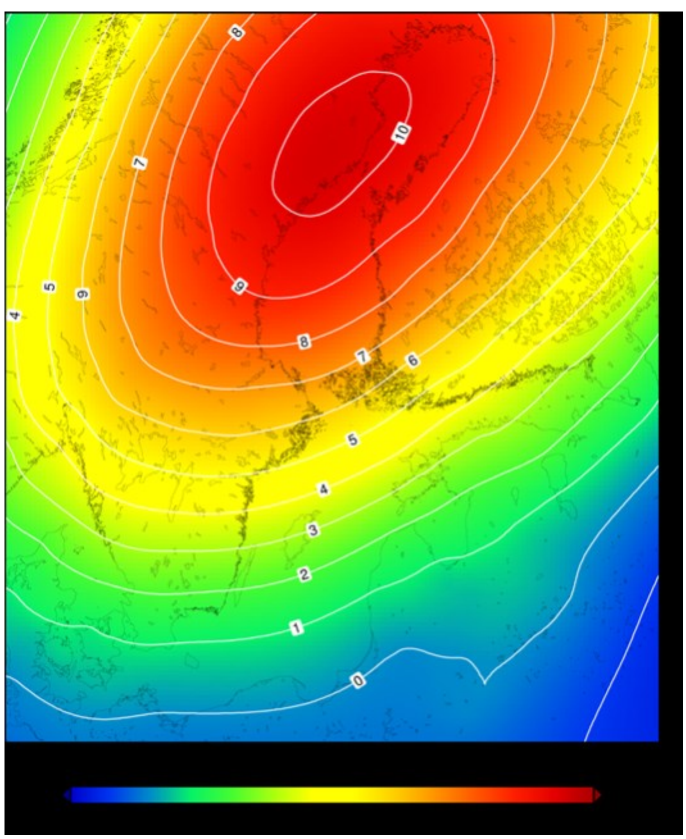


Figure 1: *Land uplift in Fennoscandia according to the NKG2016LU model (Vestøl et al. 2019)*

The MSL-based chart datum is only well-known at the tide gauge location. With increasing distance it is hard to predict the actual height difference of the sea level with respect to the tide gauge location. The uncertainty of the sea level predictions may reach the order of several decimeters and limits the accuracy of the depth information in nautical charts. Updating nautical charts and references for different kind of water level information implied large work in the past, especially in Sweden and Finland (see ***Section 4***).

Meanwhile, digital maps, satellite positioning and wireless internet have fundamentally changed the way we navigate in daily life. Regarding marine traffic, electronic nautical charts (ENC) replace paper charts. GNSS is used in hydrographic surveying not only to define the position in the horizontal direction but also in the vertical direction when measuring depths. To get the benefits of GNSS, the chart datum has to be well defined and compatible with GNSS positioning.

Modern hydrography is more than ship navigation and charted depths with respect to tide gauges. Spreading from environmental protection to economy, novel applications are typically multidisciplinary connecting the fields of hydrography and modern space-borne geodesy with for instance geophysics and telemetry. This is stimulated by increasing use of the sensitive coastal zones (e.g., offshore energy, safe vessel navigation, etc.). Another most relevant example is, of course, the monitoring of (global and regional) sea level changes by combining classical and modern geodetic space techniques (i.e., water level stations, geometric levelling, satellite altimetry and GNSS). Finally, GNSS based 3-D navigation becomes more common in commercial shipping and accuracy requirements of the depth information will increase. Future marine traffic will potentially see autonomous vessels which will require remote GNSS-based surveillance of the under keel clearance (UKC).

All these applications rely on observations on or of the sea surface by modern space-geodetic techniques. Thanks to GNSS and satellite radar altimetry, the height and the changes of both sea surface and land surface can nowadays be observed in a global Earth-fixed three-dimensional coordinate system with high spatial resolution. Heights obtained from these 3-D coordinates are related to a mathematical defined global mean earth ellipsoid, which can differ as much as 100m from mean sea level. Therefore, the ellipsoidal GNSS heights are not directly suitable for the most practical applications and have to be transformed to a meaningful physical height reference surface (HRS). This enables to realize a datum for nautical charts based on a geodetic height reference surface (see ***Section 3***).

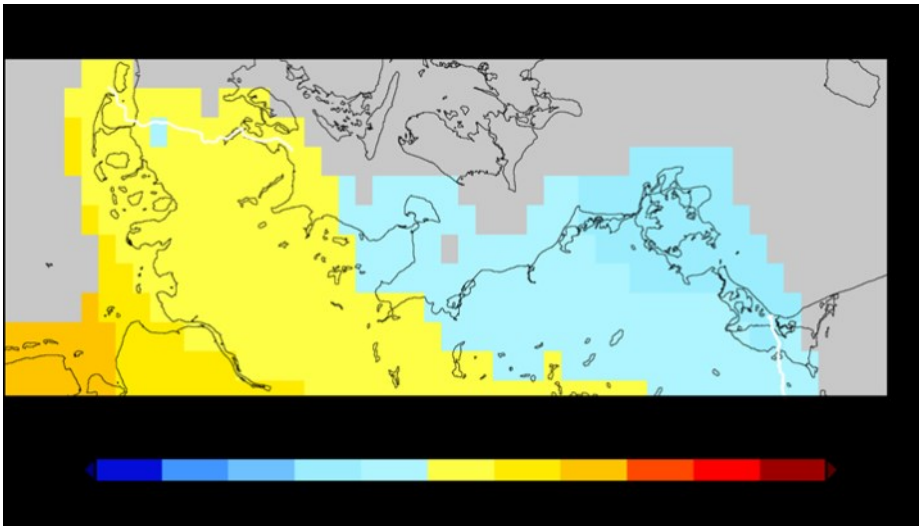
For practical applications on land, the use of GNSS-based height determination together with a compatible model of the HRS (called geoid in geodesy) have become standard and have replaced classic surveying techniques for height determination (mainly geometric levelling) in many geodetic applications. The European spatial and vertical reference systems

⇒ European Terrestrial Reference System 1989 (ETRS89) and

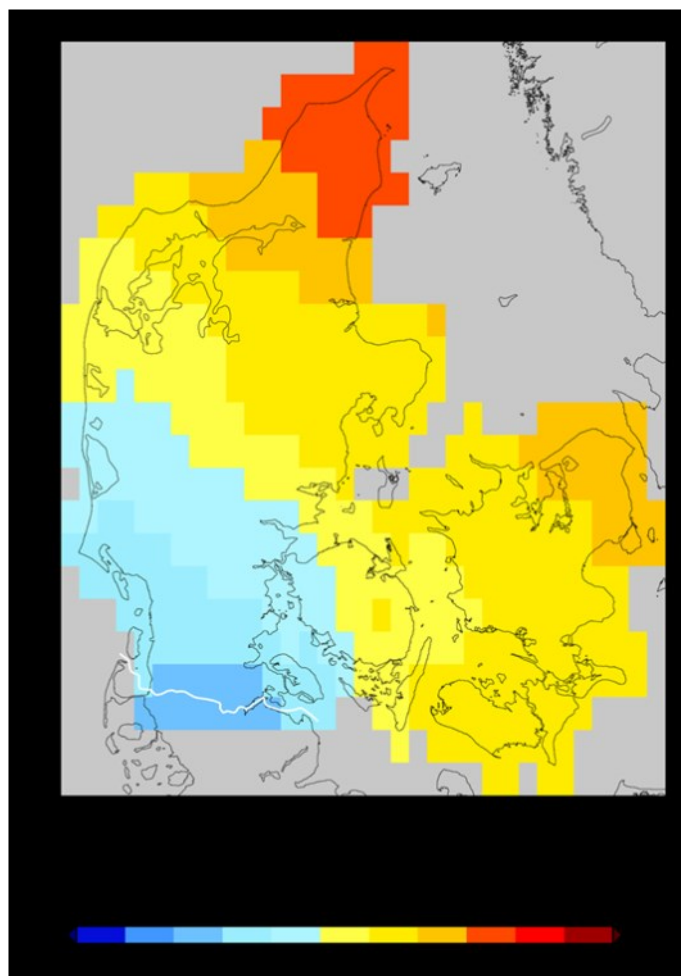
⇒ the European Vertical Reference System 2000 (EVRS2000)

are well developed and widely distributed. They are part of the INSPIRE directive of the European Commission and are supported by the member states. The respective national geodetic infrastructures have either adopted these reference frames or are in very close agreement to it (see ***Table 1*** and ***Figures. 2a-e***). The same reference systems and technologies are already in use out at sea to reference modernized hydrographic surveys.

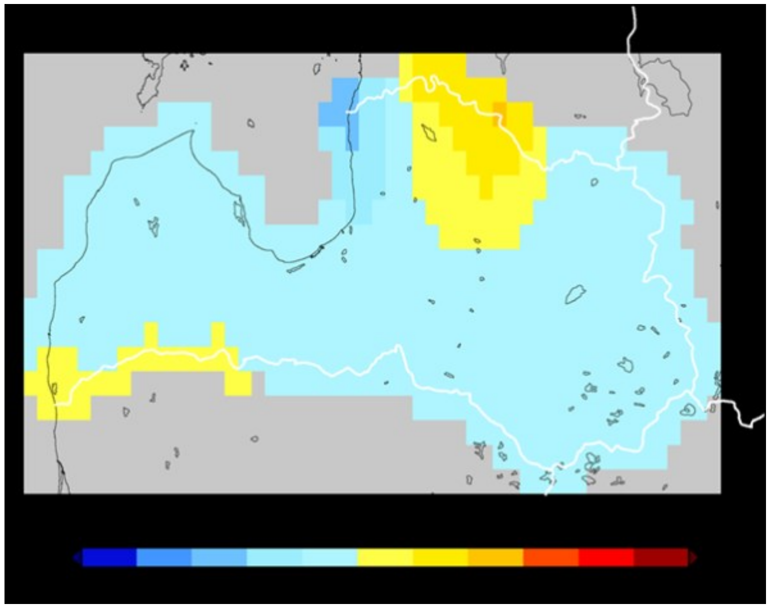
Figure 2 (a-e): *Examples of differences between national heights and zero-tide EVRF2019* *heights.*



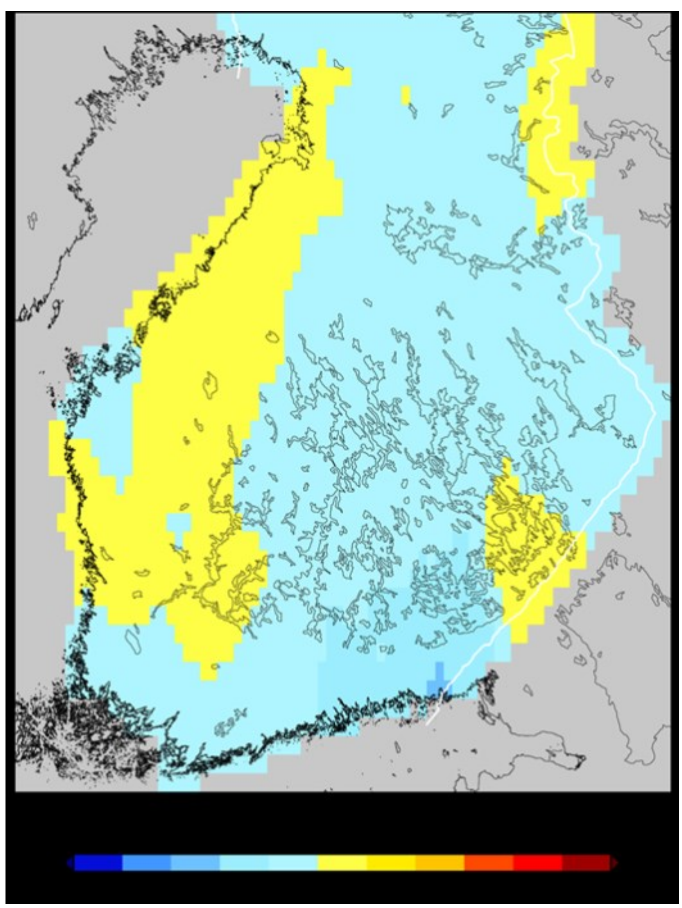
a) Height differences going from the national height reference frame of Germany (DHHN2016, north of the 53.5° parallel) to zero-tide EVRF2019 (mean –1 mm; min. –8 mm; max. +4 mm)



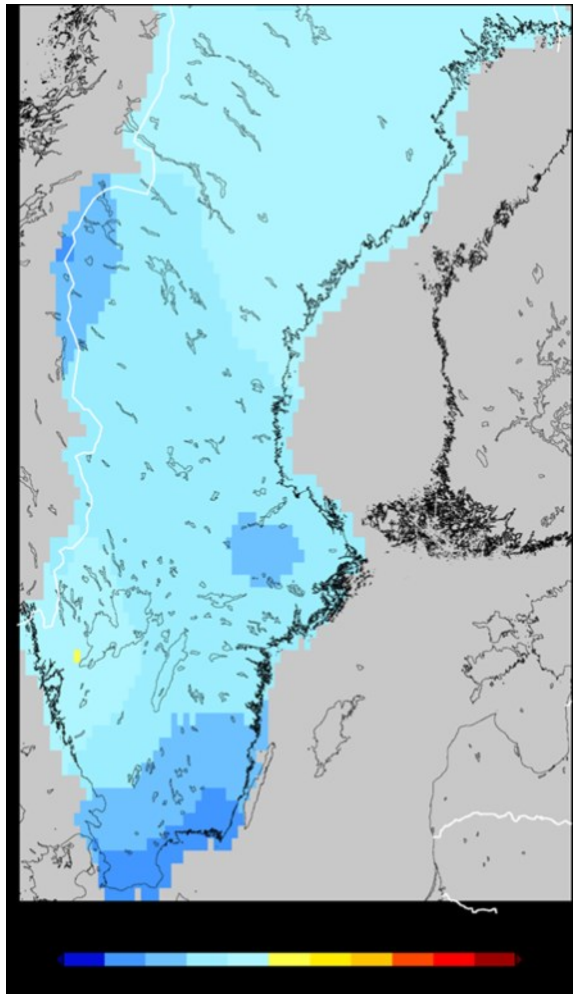
b) Height differences going from the national height reference frame of Denmark (DVR90) to zero-tide EVRF2019 (mean +1 mm; min. –12 mm; max. +13 mm)



c) Height differences going from the national height reference frame of Latvia (LAS-2000,5) to zero-tide EVRF2019 (mean –3 mm; min. difference –12 mm; max. +5 mm)



d) Height differences going from the national height reference frame of Finland (N2000) to zero -tide EVRF2019 (mean –3 mm; min. difference –11 mm; max. difference +0 mm)



e) Height differences going from the national height reference frame of Sweden (RH 2000) to zero-tide EVRF2019 (mean –7 mm; min. –19 mm; max. –2 mm)

Keeping the aforementioned developments in mind, the common reference level Baltic Sea Chart Datum 2000 (BSCD2000) has been specified with the aim to

⇒ replace the existing variety of reference levels by a seamless chart datum definition for the entire Baltic Sea;

⇒ simplify the determination and use of bathymetric charts by using the existing European geodetic standards (European Terrestrial Reference System 1989 and European Vertical Reference System 2000) and to make the marine infrastructure of the Baltic Sea fully interoperable with the national geodetic infrastructure, namely the national satellite-based positioning services (e.g., SAPOS, SWEPOS, FinnRef) and the national height systems; thereby

⇒ provide an optimal support for current and future marine GNSS aided applications and

⇒ comply with future S-10X standards of the International Hydrographic Organization (IHO).

In particular, the main benefit for the mariner is a seamless transition from chart to chart, from country to country, and from sea to land, based on a unified height datum. This comes at the "price" of potentially changed reference levels in harbors and shifted charted depths (see ***Sections 3 and 4***). Wherever possible, these changes will be introduced together with major updates of anyway outdated map sheets.

2. Organisational background for the establishment of the BSCD2000

BSCD2000 was initiated by the Baltic Sea Hydrographic Commission (BSHC). The BSHC (http://www.bshc.pro) is an integrant part of the International Hydrographic Organisation (IHO), promotes the technical cooperation in the domain of hydrographic surveying, marine cartography and nautical information among the neighboring countries of the Baltic Sea region. The main objectives of the Commission are the coordination of the production of the Baltic Sea INT Charts, the coordination of hydrographic re-surveys, harmonization of chart datums, harmonization of Baltic Sea ENCs, and the exchange of information and the harmonization of practices with regard to various issues related to hydrography. Its member states are visualized in ***Figure 3***.

Figure 3: *Members states of the Baltic Sea Hydrographic Commission (BSHC)*

In 2005, the Baltic Sea Hydrographic Commission (BSHC) recognized the issue of the incompatible chart datums in the Baltic Sea and established the Chart Datum Working Group (CDWG) to develop a concept of a harmonized chart datum. The CDWG (http://www.bshc.pro/working-groups/cdwg) reports to the BSHC Conferences and aims to implement the Baltic Sea Chart Datum 2000 as a common reference level in the Baltic Sea. The working group cooperates with relevant bodies, reviews the progress of national plans and proposes harmonization actions. The working group also liaises with relevant IHO bodies and studies relevant IHO resolutions and specifications. It is currently chaired by Mr Thomas Hammarklint (SMA, Sweden) with Mr Jyrki Mononen (Traficom, Finland) as ordinary secretary.

After a feasibility study, it was decided and agreed that the harmonized vertical datum will be based on the European Vertical Reference System (EVRS). In September 2013, the 18th Baltic Sea Hydrographic Commission Conference decided to continue the work of the Chart Datum Working Group (CDWG) and wished the harmonized Baltic Sea vertical reference to be implemented. IHO BSHC has approved the name and the adoption of the Baltic Sea Chart Datum 2000 and the abbreviation BSCD2000.

BSCD2000 has been registered as Chart Datum number 44 in the IHO Geospatial Information (GI) Registry and can therefore be used as a reference datum in all future S-100[1] products. It applies to all national realizations of the European Vertical Reference System (EVRS).

The basic prerequisite for the realization and introduction of the BSCD2000 is the determination of a model of the height reference surface with sufficient accuracy. The practical works were significantly supported by the FAMOS project (www.famosproject.eu) which was co-financed by the European Commission. FAMOS stands for "Finalizing Surveys for the Baltic Motorways of the Sea" and is part of the "Motorways of the Seas", a concept to develop European maritime traffic infrastructure within the framework of the Trans-European Transport Network (TEN-T) policy. Major activities within FAMOS consisted of the coordination and execution of shipborne campaigns to measure the gravity data needed to compute an improved geoid model as the HRS for the BSCD2000, as well as the computations of the geoid[2] model itself.

3. Definition and realization of BSCD2000

In the following, only a general overview shall be given from the user's perspective. For the full geodetic detail, the reader is referred to the BSCD2000 paper (Ågren et al., 2019).

> *The first of the two most important characteristics of BSCD2000 is that it is not anymore defined with respect to the (changing) local mean sea level (MSL).*

Instead, a well-defined uniform and accessible height reference surface (HRS) is used that is equal to the distinct equipotential surface of the Earth's gravity field called the *geoid*.

The instantaneous sea surface is deflected from the above equilibrium surface due to ocean dynamics (induced by currents, temperature, salinity variations, wind etc.) in combination with the coastal shape and bathymetry. The long-term average of these deflections is not zero, hence the mean sea surface is offset from the geoid. The static part of this difference, which can reach up to approximately ±2 m worldwide, is called mean dynamic topography (MDT). It can be observed and computed either from oceanographic models or from combined space-geodetic observations (altimetry and gravity satellite missions). In the Baltic Sea, the MDT is generally positive (compared to the MSL/MDT of the North Sea) with a slope of approx. 30 cm towards the North-east, corresponding mainly to decreasing salinity. ***Figures 4 and 5*** show examples for a geoid model and a space-geodetic MDT model of the Baltic Sea, respectively.

1 - The S-100 Standard (https://iho.int/en/s-100-universal-hydrographic-data-model, last access May 15, 2020) is a framework document that is intended for the development of digital products and services for hydrographic, maritime and GIS communities. It comprises multiple parts that are based on the geospatial standards developed by the International Organization for Standardization (IHO).

2 - The geoid describes the undisturbed sea level in equilibrium as if there were no external forces (wind, currents, temperature, salinity). In geodesy, it is the classic height reference surface for the realization of "heights above sea level" on land.

This change of chart datum to a zero level that is a little offset from MSL may at first glance appear unnatural to the mariner. However, the advantage of the geoid-based definition of the chart datum is that the geoid is virtually independent from changes of sea level and can be determined to high accuracy without sea level observation (see next paragraph). Thus, as motivated in Section 2, the geoid provides the required unified reference surface in order to monitor absolute and relative sea level changes by combination of space-geodetic techniques (GNSS, satellite altimetry) and classic local sea level observations along the coast (water level stations, geometric levelling). This holds true also for the Baltic Sea where global sea level rise (i.e., dynamic ocean) is contrasted by postglacial land uplift (i.e., dynamic Earth), since the latter effect can be modelled with high accuracy.

Geoid-based HRS are realized by so-called geoid models, i.e., gridded values of the geoid height with respect to the reference ellipsoid used for GNSS applications. They can be computed from gravimetric measurements with a typical internal standard uncertainty of 1-2 cm in areas with good gravity data coverage. For practical use, the gravimetric geoid models are fitted to the ellipsoidal and physical heights of co-located GNSS and levelling benchmarks in order to become compatible with the national height system realizations. The HRS for the BSCD2000 will be an adopted quasigeoid[3] model referenced to a common zero level.

In this respect, *BSCD2000 replaces the so-far heterogeneous and inconsistent historical MSL realizations between countries, or even between map sheets or harbors within the same country.*

The computation of this geoid model was stimulated by preparation works co-financed by the EU. Acquisition and measurement of the necessary data and the computation of interim (i.e. preliminary) geoid models were organized and performed within the project “Finalizing Surveys for the Baltic Motorways of the Sea” (FAMOS). Unfortunately, the last phase of the FAMOS project (2019 -2020) could not be realized, so that the finalization of the BSCD2000 HRS is now coordinated by the CDWG and planned for the end of 2022.

> *The second most important characteristic is the new and unified zero level. BSCD2000 will be linked to the Normaal Amsterdams Peil (NAP).*

NAP is the zero level for the European Vertical Reference System (EVRS) but also for most countries around the Baltic Sea. All states formerly referring to the Kronstadt datum have changed their national height systems or are in transition to change to the EVRS, except for Russia[4]. Numerically, these national realizations of the NAP coincide at the centimeter level, as demonstrated in Figs. 2a-e and Table 1 in comparison with EVRF2019, the last official release of the European height system EVRS (Sacher et al. 2019). Consequently, the respective national height systems can be considered as ready-to-use realizations of the BSCD2000 within its specification (overall standard uncertainty better than 5 cm, sufficient for the typical precision of charted depths; see further Ågren et al. 2019).

~~Likewise, the HRS of the BSCD2000 will be al~~igned to the respective national HRS on land with

3 - The conceptional difference between geoid and quasigeoid is a geodetic subtlety that is only relevant on land at high altitudes.

4 - Only for Russia, simple transformation models between national heights and BCSD2000 will be necessary, probably by means of local datum shifts for the areas of Oblast Kaliningrad and the Gulf of Finland/St. Petersburg.

smooth transitions from country to country. The ellipsoidal height part of the quasigeoid model is referenced to the GRS 80[5] ellipsoid (Moritz 1980) of the national realizations of the European spatial reference system ETRS89 used for GNSS, whereas the physical height part is again consistent with the national levelling heights[6].

By that, BSCD2000 is inherently connected with the existing geodetic standards for height determination (European reference systems ETRS89 and EVRS), making it compatible with the national geodetic infrastructure, such as GNSS positioning services. In particular, the connection to the height systems on land facilitates the planning and construction of offshore projects mainly in the energy sector.

In other words, BSCD2000 shares the "common European zero levels for levelling and GNSS".

Hence, BSCD2000 for the first time enables seamless cross-border use of real-time GNSS positioning in combination with ENC for ship navigation in the Baltic Sea. This also forms the foundation of novel techniques that are emerging under the term "Sea Traffic Management". Based on real-time GNSS, high-resolution ENC and unified water level forecasting, the ship can continuously monitor its current and projected UKC without echo sounding. One highlight application of this "situation-aware navigation" that also has been studied within the EU co-funded FAMOS project are ship routes optimized for fuel efficiency, because the fuel consumption of a large vessel increases considerably for low UKC due to the hydrodynamic squat effect.

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5 - The geometric shapes of the GRS 80 and the WGS84 ellipsoids are identical at the sub-mm level.

6 - The Scandinavian countries are particularly affected by postglacial land uplift. BSCD2000 assumes the land uplift epoch 2000.0. This means that all relevant coordinates and quantities (ellipsoidal heights, physical heights, quasigeoid heights) refer to this common epoch, as opposed to the previously inconsistent MSL epochs. Compared to that major geophysical effect, the impact of expert-level details – such as treatment of the permanent tide – are within the uncertainty specifications of BSCD2000 and the national EVRS realizations, so that they are not discussed in this paper. For such geodetic details, the reader is again referred to the BSCD2000 specification paper (Ågren et al. 2019).

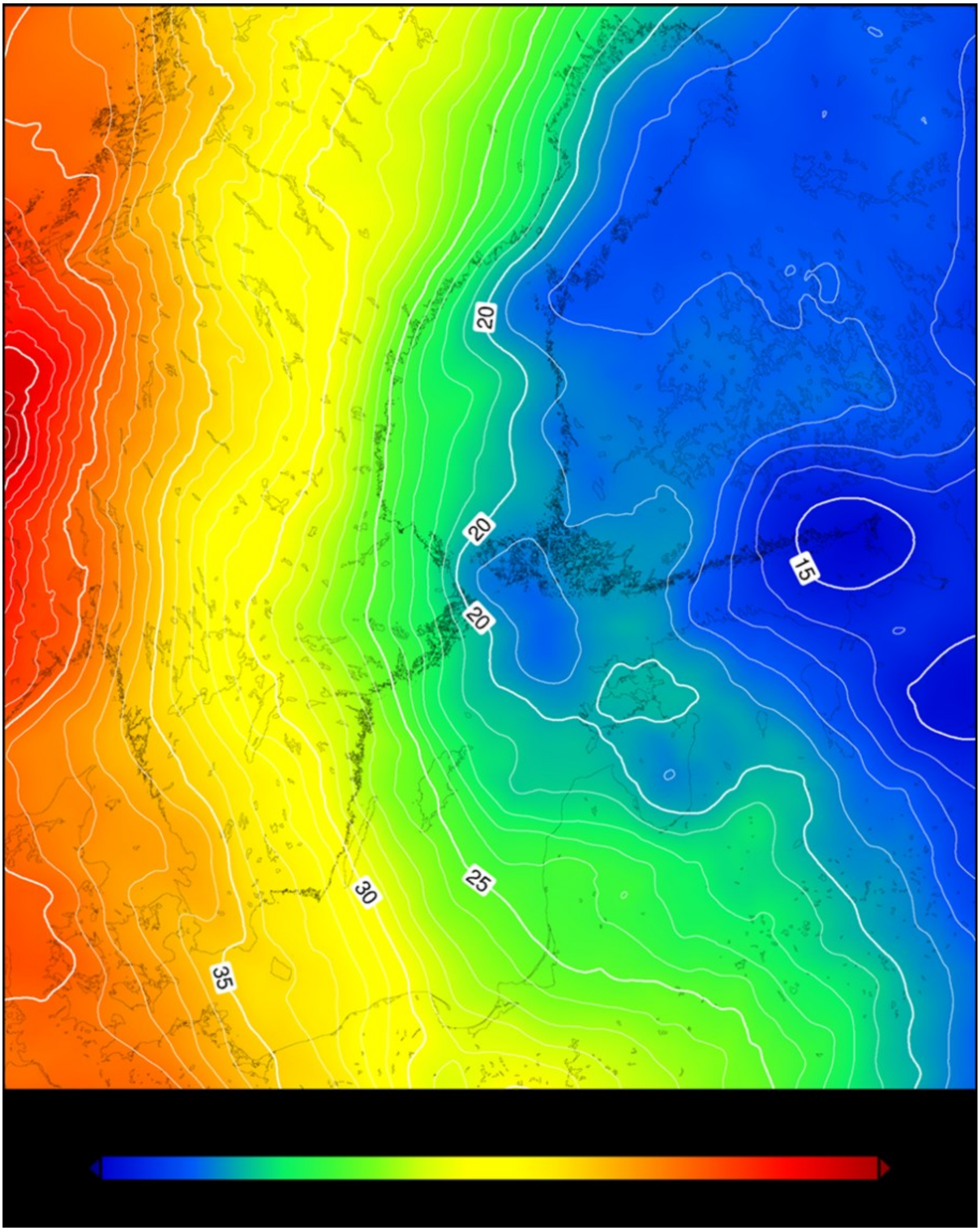


Figure 4: *LM6a, an interim geoid model for the FAMOS project by Jonas Ågren (Lantmäteriet)*

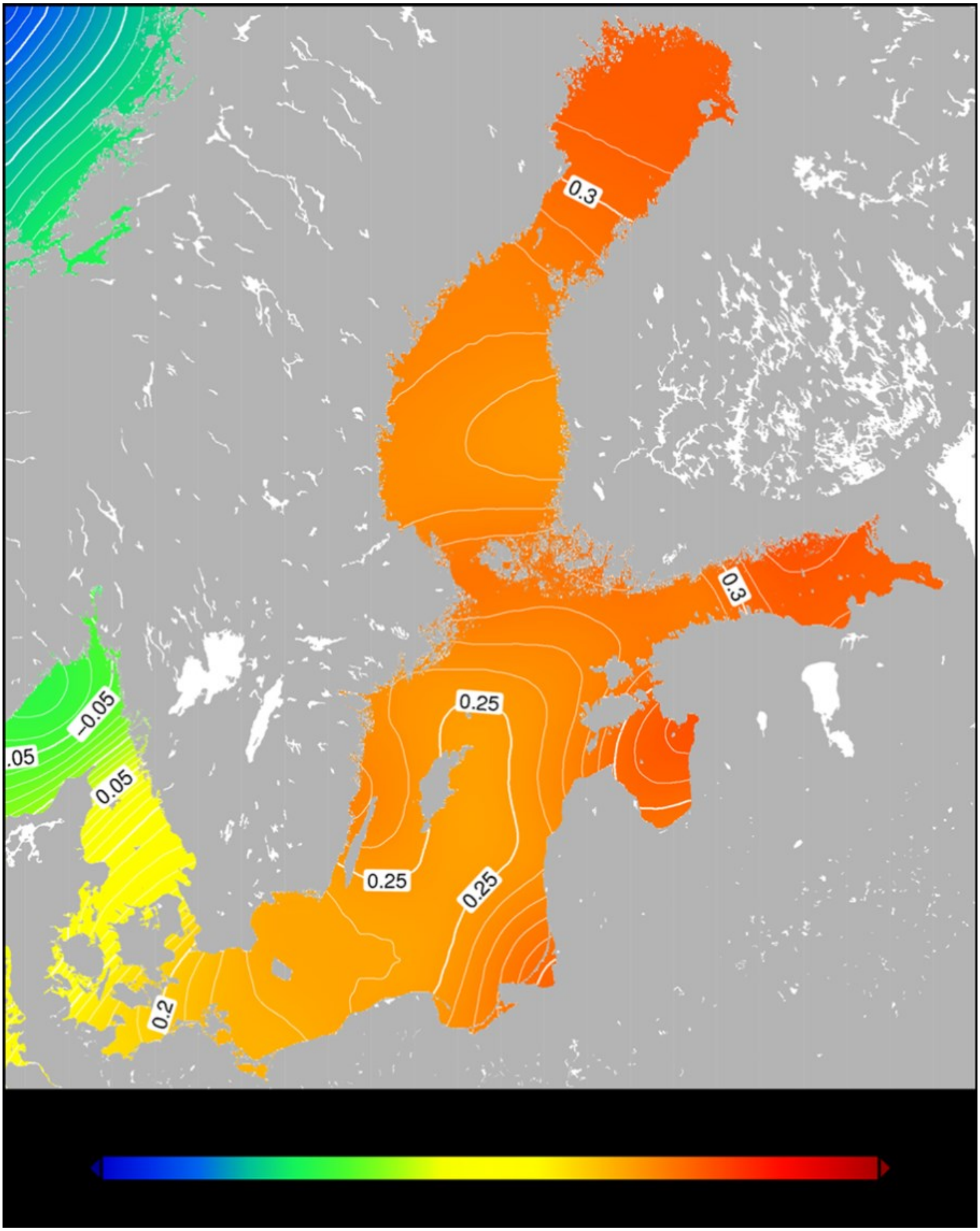


Figure 5: *DTU19MDT (Andersen and Knudsen 2009), a specimen for a geodetic model of the mean dynamic topography, over the Baltic Sea. It can be considered as a smooth proxy for the height of the recent MSL above the BSCD2000 height reference surface.*
The model was derived by combining multi-mission altimetry over a 20 year period with the latest state-of-the-art global potential model derived using the GOCE satellite. Consequently, the model is only a proxy for wavelength longer than 100 km. For this plot, the zero level has been shifted approximately from a global geoid to NAP to roughly match the definition of the BSCD2000.

4. Practical implications

New nautical products that use BSCD2000 are identified by the chart datum name BSCD2000$^{<X>}$, where $^{<X>}$ denotes the respective national height system realization according to ***Table 2*** (e.g., BSCD2000^{RH2000} for Sweden).

The main consequence for the mariner is that the *charted depth* in BSCD2000 changes by a constant value compared to the old zero level. The offset is individual per country or per map sheet, depending on the former MSL-related chart datum. In most cases, this offset will be negative, since the new zero level of the BSCD2000 is in general below the present day MSL for the Baltic Sea (see ***Figure 6*** for a generalized visualization and ***Figure 7*** for a map of the national MSL realizations currently in use). However, for charts of areas strongly affected by postglacial uplift and referring to very old MSL realizations, the change to BSCD2000 may be considerable. ***Figure 1*** gives an impression of the land uplift rates according to the model NKG2016LU (Vestøl et al. 2016).

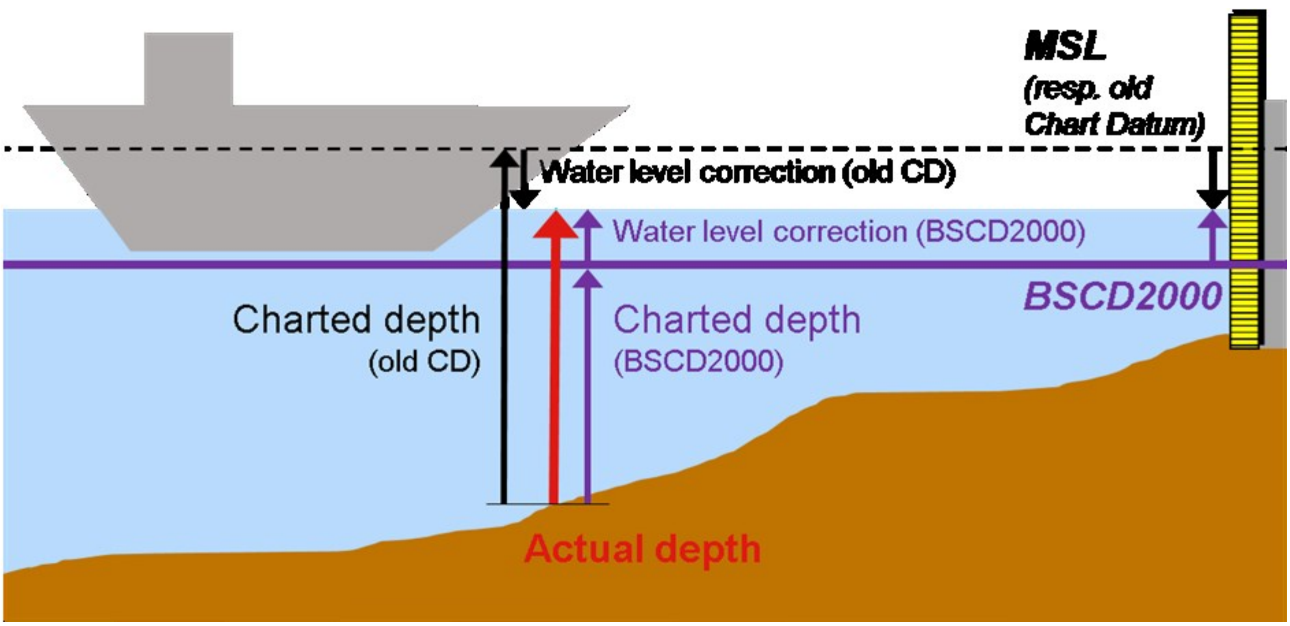


Figure. 6: *Schematic cartoon of the old MSL-based chart datum and the new BSCD2000*

At the same time, *real-time water level information* (water level observations, corrections to the charted depths, forecasts, etc.) will also be changed accordingly to comply with the new chart datum. This also allows for a better and easier monitoring and prediction of the current and future sea states out at sea, since real-time oceanographic models can be simply interpolated (***Figure 8***), whereas switching between the sometimes far-distant mareographs and their local references may introduce a large error margin (***Figure 9***).

The transition from the numerous MSL-based chart datums of each country to BSCD2000 is a complex and stretched process from the first decisions to the final implementation in the chart products. In particular, paper charts need longest to be switched due to the long production cycles. Some countries, like Estonia, have already informed mariners about the changes to BSCD2000 and have published the first products. Others, like Denmark, are about to formally adopt BSCD2000 as the name of their chart datum without having to actually change their charted depths. Therefore, this section only gives an overview about the general situation in the respective countries. ***Table 2*** summarizes the national geodetic reference frames, positioning services and HRS realizations that can be used with BSCD2000. Regularly updated details about the implementation status as well as instructions for users, e.g. leaflets, are provided via the CDWG website (http://www.bshc.pro/working-groups/cdwg).

In ***Sweden and Finland***, a *calculated MSL* has been used as reference level (chart datum) for nautical charts and water level information. The reference level for regularly updated epochs (estimated present-day MSL) was estimated from long time series of annual mean values of mareograph observations. Depths from printed charts needed to be converted semi-automatically by means of a correction formula in order to correct for the time difference and to make the charted depth compatible with the provided water level information. As motivated in ***Section 2,*** this two-step approach implied a lot of work to keep the nautical products updated and consistent. At the same time, it was not straightforward and error-prone for the mariner.

Thus, decisions to make a transition to BSCD2000 in Sweden and Finland have come a long way. In Sweden, both water level information and 50% of all nautical charts are now using BSCD2000. In Finland, part of the bathymetric and chart data have already been transformed to BSCD2000. Water level information is ready to be provided in BSCD2000 when first charts will be published in the new datum. ***Figure 7*** details the estimated height of the *current calculated MSL* relative to BSCD2000 for selected mareographs in Sweden and Finland.

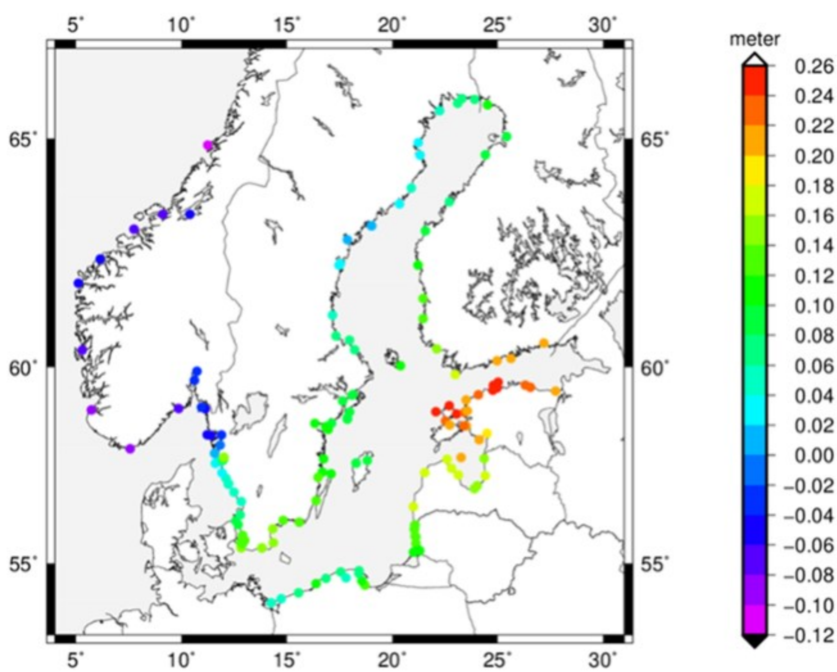


Figure. 7: *Differences between the reference levels of the old national chart datums with respect to Baltic Sea Chart Datum (BSCD2000). In Sweden and Finland, the old reference levels are equal to the calculated MSL in the year 2020 (according to different national conventions). The values from Norway shows the MSL over the period 1996-2014, relative BSCD2000^{NN2000}. In Estonia, Latvia and Lithuania, the Kronstadt reference level is used as old chart datum. In Poland, the local Polish Height System Amsterdam NH$_{55}$ is used as chart datum. Notice how postglacial rebound reduces the magnitude of the calculated MSL relative BSCD2000 in the Bay of Bothnia; it is now just a few cm close to the location of maximum uplift. The values are taken from BOOS (2020).*

In the Baltic Sea regions of ***Denmark***, a reference level close to the national height system DVR90 is already being used as chart datum, which can now be considered as a national realization of the BSCD2000. This means that for a user in Denmark nothing changes and the official national geoid model can still be used at sea.

Likewise, chart datum and MSL observations in ***Germany*** have traditionally been linked to the national height system. In 2016, the previous realization DHHN92 was replaced by DHHN2016. Both old and new realization are consistent with the EVRS, and the differences between the two are small and well within the specifications of the BSCD2000. Germany is now in the process to formally adopt $\text{BSCD2000}^{\text{DHHN2016}}$ as the chart datum name in its Baltic Sea products, yet without actual changes for the user.

In ***Norwegian*** waters, on southern Skagerrak, a reference 20 cm below Lowest Astronomical Tide (LAT) is used as chart datum.

On the eastern side of the Baltic, in ***Estonia, Latvia, Lithuania and Poland***, the transition from Kronstadt-based datums into the new system has come a long way, even if the old and new reference systems will be working in parallel for many more years to come. The transition into the new system for the paper charts will take longest time to change.

Table 1: Differences between EVRF2019 (zero-tide) and EVRS-compatible national height reference frames in mm.

Country	Mean	Std. dev.	Min.	Max.
Denmark	+1	6	–12	+13
Estonia	–7	8	–22	+16
Finland	–3	2	–11	+0
Germany north of 53.5° latitude	–1	4	–8	+12
Latvia	–3	2	–12	+6
Lithuania	–4	5	–11	+5
Norway south of 60.0° latitude	–14	7	–42	+3
Sweden	–7	3	–19	–2

Table 2: National reference frames and services complying with BSCD2000 (as of May 2020, without responsibility for correctness).

Country	3-D position	Physical height	Height ref. surface	GNSS pos. service
Denmark	EUREF89	DVR90	DKgeoid12	GPSnet.dk, SmartNet
Estonia	EUREF-EST97	EH2000	EST-GEOID2017	ESTPOS
Finland	EUREF-FIN	N2000	FIN2005N00	FinnRef
Germany	ETRS89/DREF91 Realization 2016	DHHN2016	GCG2016	SAPOS
Latvia	LKS92	LAS2000,5	LV14	LatPOS
Lithuania	LKS94	LAS07	LIT15G	LitPOS
Norway	EUREF89	NN2000	HREF2018B_NN2000	SATREF
Poland	PL-ETRF2000	PL-EVRF2007-NH	PL-geoid-2011	ASG-EUPOS
Sweden	SWEREF 99	RH2000	SWEN17_RH2000	SWEPOS

5. Summary and Outlook

So far, several countries around the Baltic Sea are using BSCD2000 as the common reference level for nautical charts as well as for water level information. According to the time schedule and the roadmap (http://www.bshc.pro/media/documents/CDWG/CDWG+RoadMap.pdf), the plan is to implement the common reference level until 2023. Almost all countries have taken the necessary decisions to move further in the implementation process, however this ambitious goal will most probably not be reached by all countries. For paper charts, the implementation will take longer time and there will be a significant transition period that will last for several years after 2023. Hydrographic offices will publish information concerning the national plans and progress of implementation since there will be differences in schedules of publication of charts and water level information between countries.

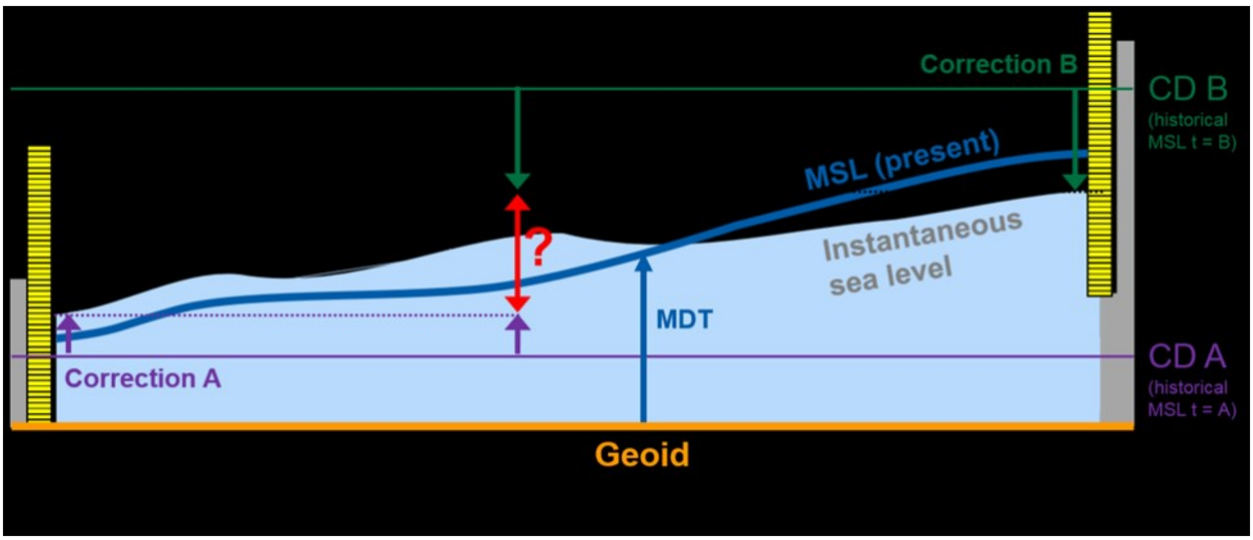
There are many benefits to be achieved with the implementation of BSCD2000. All depth and water level information will be provided in the same datum within the whole Baltic Sea. This eliminates the confusion between different chart datums and makes data transfer between national Hydrographic Offices and other organizations safer and easier, thereby contributing to safety of navigation in the highly frequented Baltic Sea. Further, on it enhances wider and easier use of depth data and promotes utilization of future navigation systems based on International Hydrographic Organization (IHO) S-10X standards.

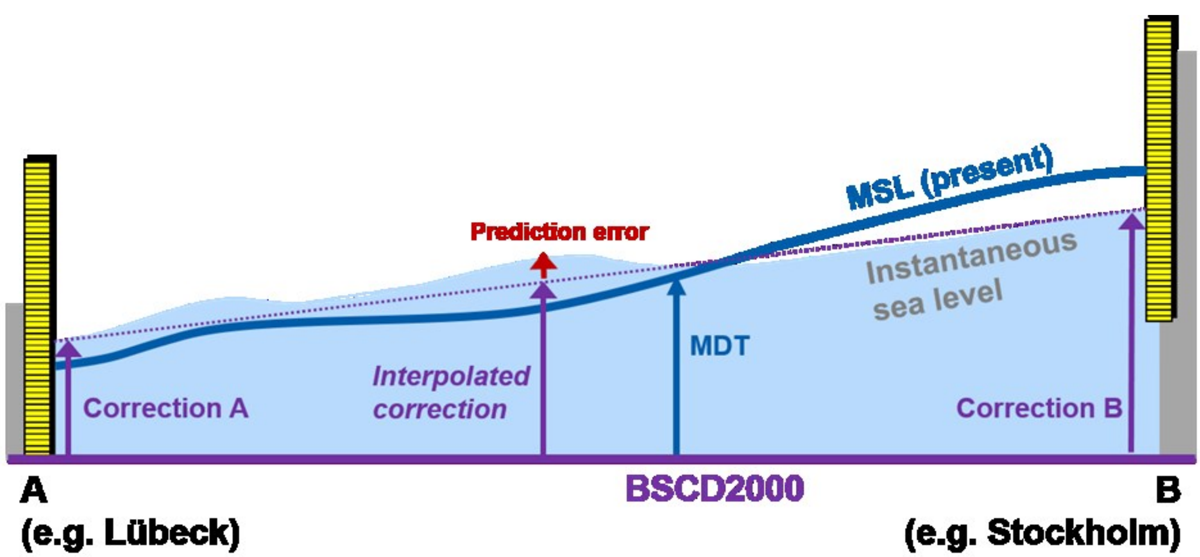
BSCD2000 is based on the common European Vertical Reference System to which many national height systems are linked. Thus, depths on sea and heights on land will be referenced to the same reference system, facilitating e.g. offshore engineering in the sensitive coastal zones of the Baltic Sea. BSCD2000 can be used with GNSS applications by means of a consistent height reference surface, which will be realized by a high-resolution geoid model. The computation of this model was promoted by the EU co-financed project FAMOS and is now being finalized. It is planned to adopt the "FAMOS geoid" as the recommended physical height reference surface (HRS) for the BSCD2000 and make it available at no charge latest 2023. Compared to the national HRS, that are also compatible with BSCD2000 and can still be used (see ***Table 2***), this model will provide the advantage of a seamless transition across the national borders.

Finally, BSCD2000 facilitates future applications that require an integrated spatial reference at sea and, thus, responds to the growing interrelationships between disciplines like hydrography, oceanography, geodesy, geophysics, climate research, coastal protection, and traffic management.

Fig.ure 8: *Illustration how mismatching chart datums affect the prediction of the actual water level correction between harbors*

Figure. 9: *Illustration of consistent water level correction with BSCD2000.*





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7. Authors Biography

Joachim Schwabe is a scientific staff member of the unit “Integrated Spatial Referencing” at the German Federal Agency for Cartography and Geodesy (BKG). He graduated as a geodesist from the Technische Universität Dresden (TUD) in 2008 and finalized his PhD thesis on regional geoid modeling in the polar regions in 2015. An opportunity to assist the computations for the quasigeoid model GCG2016 led him to the BKG, where he is now contact person for the GCG models and GNSS-based height determination. E-mail: joachim.schwabe@bkg.bund.de

Jonas Ågren is associate professor in geodesy and senior lecturer at the University of Gävle in Sweden. He is also part time senior geodesist at Lantmäteriet, the Swedish mapping, cadastral and land registration authority. He received his PhD degree in physical geodesy at the Royal Institute of Technology in Stockholm (KTH) in 2004. Since then he has worked with geoid modelling, height systems and gravimetry in Sweden and the Nordic/Baltic countries. He was the chairman of the working group on geoid and height systems of the Nordic Geodetic Commission (NKG) between 2010 and 2018, and leader of FAMOS activity 2 (Harmonising vertical datum/Improving vessel navigation for the future) between 2015 and 2018.E-mail: jonas.agren@hig.se

Gunter Liebsch is head of the unit “Integrated Spatial Referencing” at the German Federal Agency for Cartography and Geodesy (BKG), dealing with the German and the European height systems, GREF (GNSS reference station network in Germany) and the national quasigeoid model GCG. He graduated as a geodesist from the Technische Universität Dresden (TUD) in 1990 and finalized his PhD thesis on the processing and use of water level time series for geodetic and geodynamic applications in the Baltic Sea in 1997.E-mail: gunter.liebsch@bkg.bund.de

Patrick Westfeld is head of German Hydrographic Office‘s R&D section “Geodetic-hydrographic Techniques and Systems” at the Federal Maritime and Hydrographic Agency (BSH). His activities range from conceptual issues pertaining to hydroacoustic and imaging sensor technologies, sensor integration and modeling, algorithmic development and software implementation up to and including application-specific implementation and practical transfer in the production environment. After graduating as a geodesist from the Technische Universität Dresden (TUD) in 2005, he conducted research in the fields of photogrammetry and laserscanning and finalized his PhD degree in 2012 on geometric-stochastic modeling and motion analysis. E-mail: patrick.westfeld@bsh.de

Thomas Hammarklint is the Chairman of the BSHC Chart Datum Working Group and works at the Swedish Maritime Administration (SMA). He graduated as a physical oceanographer from the Gothenburg University in 2002. He is the Swedish representative and expert in several working groups and programs related to water levels, data exchange and reference levels, such as IOC Global Sea Level Observing System (GLOSS), IHO Tidal Water Level and Current Working Group (TWCWG), NSHC Tidal Working Group (TWG) and Baltic Sea Operational Oceanographic System (BOOS). E-mail: thomas.hammarklint@sjofartsverket.se

Jyrki Mononen is an expert at the Finnish Transport and Communications Agency Traficom in the Hydrographic Survey Services. He is the ordinary secretary of the BSHC Chart Datum Working Group. He graduated as MSc in land surveying an the Helsinki University of Technology in 1995. He has been involved in chart datum definitions in Finnish nautical charts and navigational information, national specifications for hydrographic surveying and procurement of hydrographic surveys. He is Finnish representative in IHO Tides, Water Level and Currents Working Group and Data Quality Working Group. E-e-mail: jyrki.mononen@traficom.fi

Ole B. Andersen is professor in marine geodesy and head of the hydrosphere group at DTU Space at the Technical University of Denmark which is the national space institute of Denmark. His activity in the working group has been to provide satellite-based long-term estimates of mean sea level and mean dynamic topography as a supplement to and for the evaluation of the FAMOS geoids. Ole is Ph.d. from the University of Copenhagen in 1996 and has since worked on marine geodesy focusing on development of global reference surfaces for gravity and mean sea surface as well as ocean tide models. E-mail: oa@space.dtu.dk

Notes

WHAT IS HYDROSPATIAL ?

By D. Hains (President and Chief Executive Officer, H2i)
Email Address: dhains@h2i.ca

Abstract

The Oceans, coastal waters, including rivers and lakes, navigable or not, cover about 70% of our Planet... The definition of Hydrography varies from: "…*the science of surveying and charting bodies of waters, such as oceans, seas, lakes and rivers*"; and a variation of definitions, to the definition from the International Organization (IHO) in February 2020. In the last decades we have been progressing from "GRAPHIC"… to "DIGITAL"…and SPATIAL.

This Article suggests that a new word be adopted to distinguish the past analog hydrographic production chain from the present digital hydrographic data centricity, and especially for the future expansion of the role of hydrography in the world.

*NB This Article reflects only the opinion of the Author and H2i.

Introduction

Close to 400 participants gathered for the Canadian Hydrographic Conference (CHC) 2020, from February 25 to 27, in Québec City, Canada http://www.chc2020.org. The event was organized by the Canadian Hydrographic Association (CHA) with the support of the Canadian Hydrographic Service (CHS) and the sponsorship of many commercial providers of products and services related. During the opening plenary session, the author had the honour to make a dedicated presentation on "***What is Hydrospatial?***" before inviting a panel of senior figures and the audience to discuss the topic further. The following is a summary of a very engaging session.

Figure 1*: Denis Hains speaker), seated Left to Right: Dr.Mathias Jonas, Secretary General of the International Hydrographic Organization (IHO); Rear Admiral Sheppard Smith, Director of the Office of Coastal Surveys with the United States National Oceanic and Oceanographic Administration (NOAA); Dr.Geneviève Béchard, Hydrographer General of Canada, and Director General of the CHS; Dr. Ian Church, Chair of the Canadian Ocean Mapping Research & Education Network (COMREN), and Assistant Professor at the Ocean Mapping Group (OMG) of the University of New Brunswick (UNB), Canada.*

1. The issue

The session was introduced as a "hydrospatial **activism**", with the deliberate intention of provoking and initiating a discussion about acknowledging the revolution in which hydrography finds itself, and the requirement to apply a new, modern and inspirational name for our different era.

What we do and its impact is obviously more important than a word can convey. Many might not consider it so important to adopt the word "hydrospatial". We could just continue to use the word hydrography, and define and explain what is happening and the changes taking place simply as an evolution. It could be embracing and the adoption of new technologies. And also the related expansion of the scope, the role and mandate of hydrography, as we know it.

However, words are the way we express ourselves, and in particular, the way that we transmit our ideas and concepts to others. We are going through a "marine geospatial" revolution in which the concept of what we do, who we serve and the benefits of our data are changing - and this is so dramatic that it requires us to adopt a new word to describe it. We need a word that conveys the image of the modern, hi-tech, multi-role, digital data environment in which we now operate. The suggestion is that this word should be "hydrospatial!"

2. The Rationale

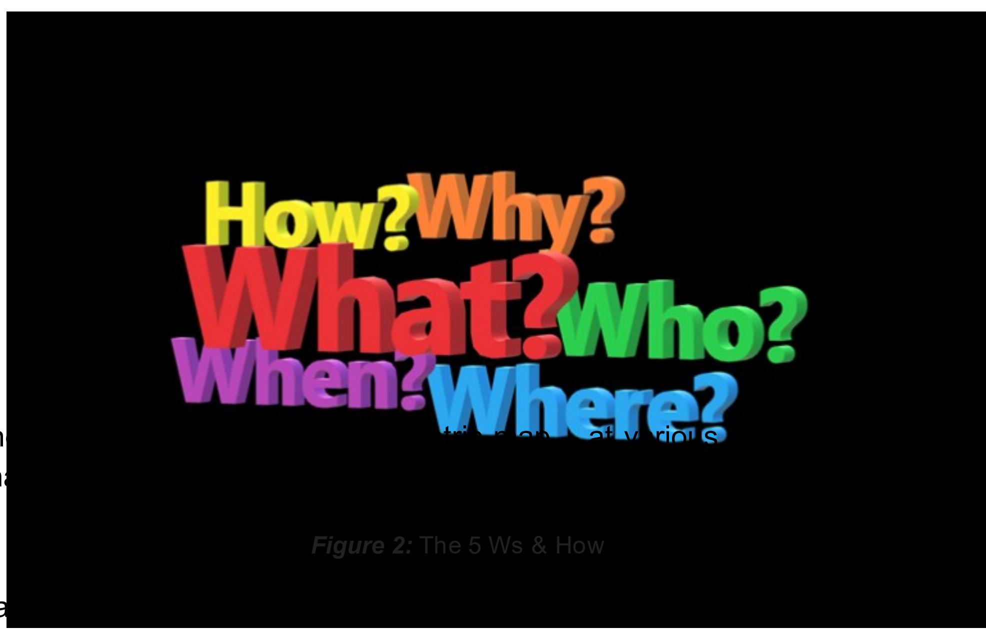


Figure 2: The 5 Ws & How

Noting that th ... allest to the largest, h ... use our sources of da ... and its scope now goes well beyond data that provides a relatively simple map of the seabed – such as in an S-57 electronic chart. It now includes all other related data, such as: marine protected areas; biological sensitive areas; traditional and environmental knowledge; real-time and forecasting for 3 dimensional currents, water levels, overhead clearances; and more (marine geospatial) data. It is much more than nautical charts and navigation. It is the pivotal element of marine spatial data infrastructures (MSDI), marine spatial planning (MSP) and the marine cadastre. It is now used and fused with data from land, coastlines, inland waters and offshore. This is the reason “why” and “when” we now need to describe it as “hydrospatial” data!

Both defence and commercial shipping users of traditional hydrographic products, data and information now seek additional information and capabilities from our data. An ever-increasing community of additional users that seek a green future through a sustainable blue economy[(1)] is joining them. They, too, are in need of more data and much more than traditional hydrographic products and services. They are looking for “marine geospatial” data and information. They are users “who” need “hydrospatial” data!

The managers of coastal zones must consider sea-level rise, coastal erosion and crustal subsidence. Nearshore, offshore and remote areas (polar regions in particular) are becoming more accessible and attractive both for natural resources and for adventurers. All this drives the need for “where” “hydrospatial” data are needed – not just nautical chart data!

We have to adopt faster all remote sensing technologies and various autonomous craft for hydrographic data acquisition (satellite, airborne, surface, underwater, etc.) as well as maintaining minimal traditional ship-based units with ever-more sophisticated sensors. These are “how” high-tech capabilities evolve and deserve to be adopted by a name like “hydrospatial” that inspires inclusion beyond traditional.

3. The Suggested Draft Definition

Figure 3: *Presenting the “what”.*

At the Conference, it was suggested that the definition of “what” hydrospatial could be based on the existing February 2020 IHO definition of hydrography. The proposed following changes were presented:

2020/02/25 - **Hydro~~graphy~~spatial** "*is the branch of applied sciences which deals with the analysis, understanding and access to static and dynamic marine geospatial digital and analog data and information, digital signals, measurement and description of the physical, biological and chemical features of oceans, seas, coastal areas, lakes and rivers from all possible available data sources in near-real time, real-time, including history and~~, as well as with~~ the prediction of their change over time. For the ~~primary~~ purpose of providing timely access to a standard, quality and the most up-to-date marine spatial data infrastructure, including the safety and efficiency of navigation~~; in support of all other~~ aquatic and marine activities, ~~including~~ for a sustainable Blue environment & economic development, security and defence, and scientific research~~, and environmental protection~~.*"

~~In addition to supporting safe and efficient navigation of ships, hydrography underpins almost every other activity associated with the sea, including:~~

- *~~Resource exploration~~*
- *~~Environmental protection and management~~*
- *~~National marine spatial data infrastructures~~*
- *~~Recreational boating~~*
- *~~Maritime defence and security~~*
- *~~Tsunami flood and inundation modeling~~*
- *~~Coastal zone management~~*
- *~~Toutism~~*
- *~~Marine science~~*

In proposing this draft definition, the focus of the role is more on analysis, understanding and judging the quality of data from multiple sources rather than simply acquiring data. The intent being to move away from a primary focus on navigation, although it is clearly included and still considered core and of key importance.

The terms "biological and chemical" were added in the definition, not so that future "hydrospatial" experts will own and manage such types of data, but they will be prepared to integrate and fuse that data into an accessible, authoritative and accurate (best quality available) up to date "marine geospatial" infrastructure. This suggested draft definition is a mouthful and is not pretending to be the final definition, it was offered as a starting point to initiate an important conversation.

The Different Perspectives and the Discussion.

Based on the opening presentation, the four panelists aired their views, including the following quotes:

Figure 4: *Dr.Mathias Jonas providing his perspective…*

The IHO Secretary-General commented: ... *“to adopt a new word and official definition in the IHO Hydrographic Dictionary S-32 would require a formal proposal put forward to the affected experts of IHO´s Hydrographic Dictionary Working Group. Hydrography is clearly going through major important changes that will require an expanded role serving an increasing group interested in the Blue Economy proponent... If this requires a new word to express the expanded scope and to address the third and fourth dimension of our undertakings, "hydrospatial" will find its way into our spoken and written language.”*

The Hydrographer General of Canada remarked: *…”showing how a new word can fill a gap by using it in sentences is more important than having it officially adopted. Just use it!”*

The Director, US Office of Coastal Surveys provided the comment: *…“The field of hydrography is changing rapidly—we have access to both a wider variety and a massive volume of relevant data than ever, and the demand for our data and expertise is growing beyond charting. This conversation about the language of identity is just the beginning. We need to also take a hard look at our education and qualifications in light of these changes.”*

The Chair of COMREN, representing Academia, said: ***…*** “ *accredited academic programs have already added material, courses and learning objectives that go beyond international requirements to adapt and keep up with the rapid technological changes in hydrography that could be qualified as hydrospatial...* ”

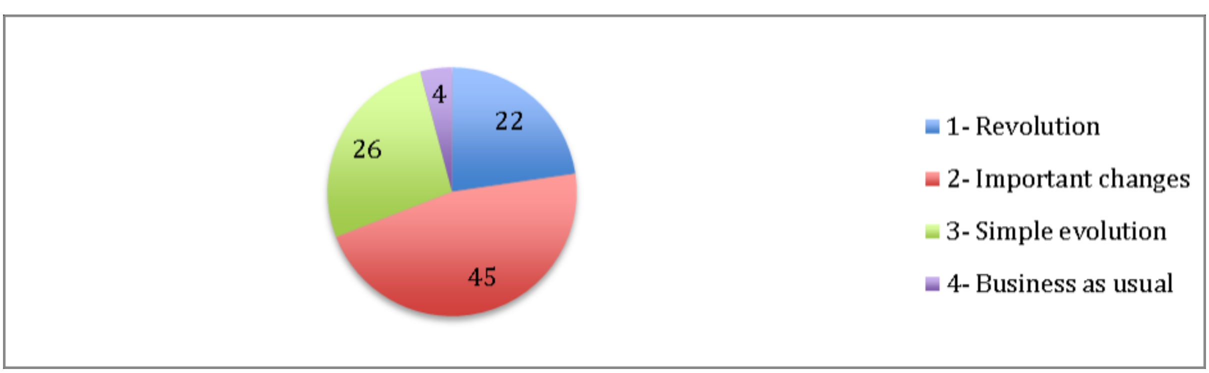
4. Engaging the Participants

***Figure 5**: Asking the contribution from the participants.*

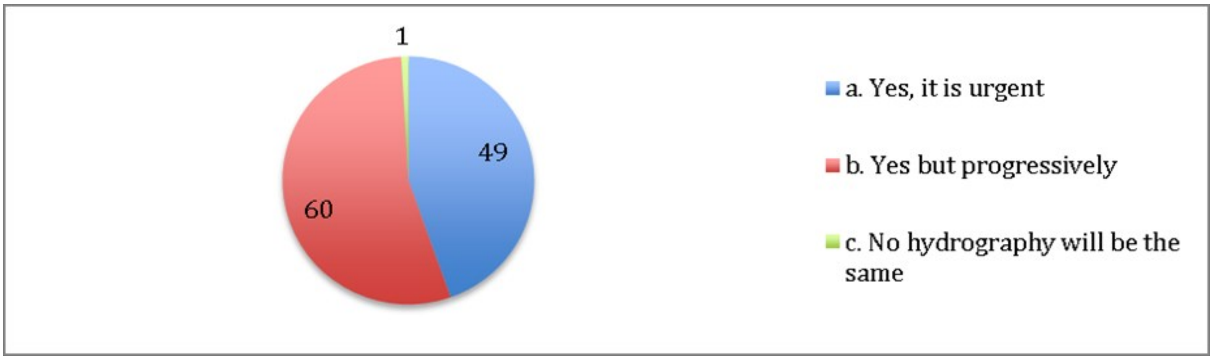
During this session we used a live voting application to engage the audience, and although not all connected to the on-line voting, a very good sample of about the third replied. In average, more than 100 voters per question replied in real time to the 6 questions, their answers below with the following results:

5. The Compiled Results

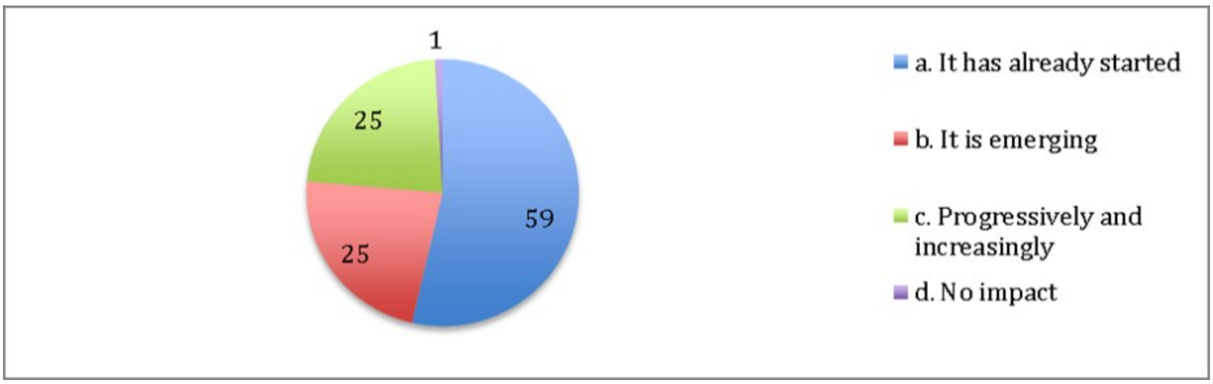
a. What is Hydrography going through? (97 votes)



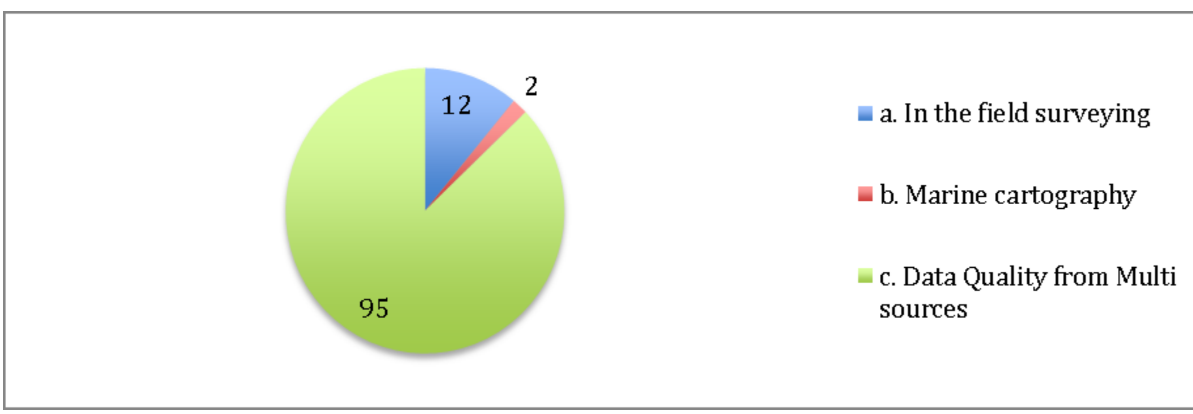
b. Should Training/Certification be adapted to rapid Technological changes? (110 votes)



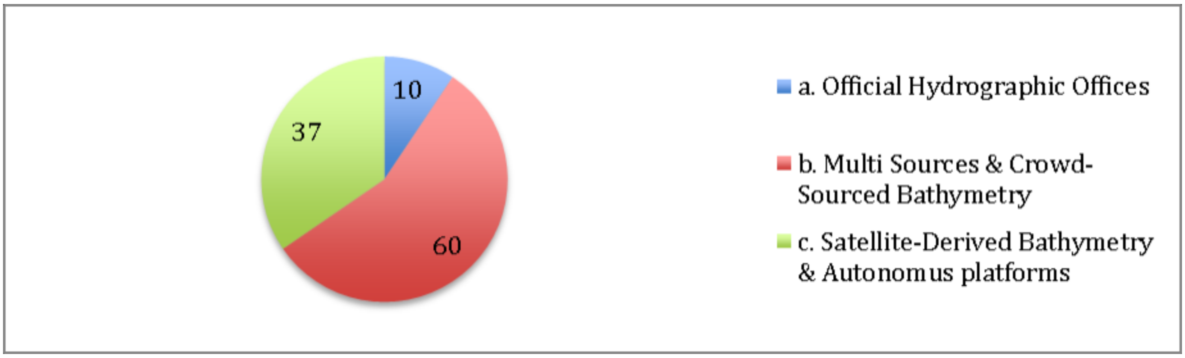
c. Do you see Artificial Intelligence & fast growing technologies impacting Hydrography? (110 votes)



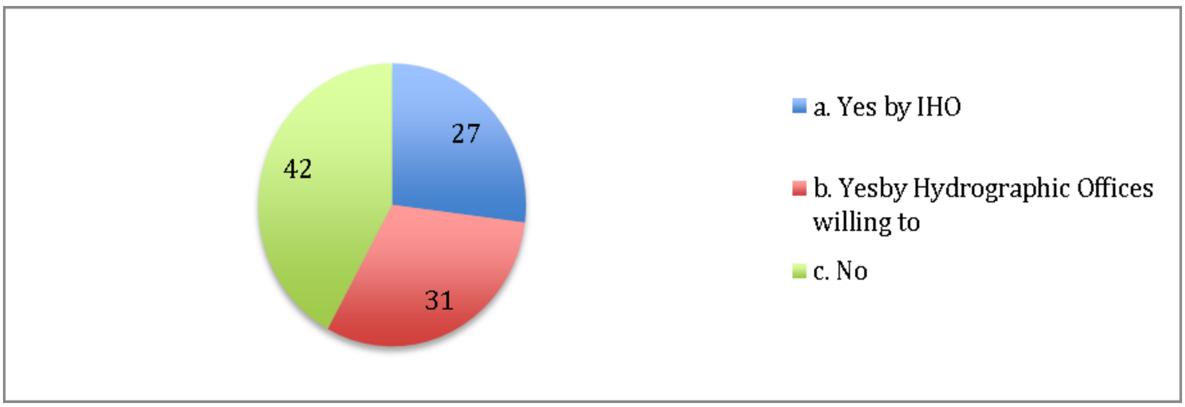
d. In the future, where do you see Hydrographer invests most of her/his time? (109 votes)



e. In the future, where do you see most Data coming from? (107 votes)



f. Do you agree to adopt "hydrospatial" officially? (100 votes)



This approach was novel in the community and allowed to draw some conclusion based on the votes and can be summarized as follow:

⇒ 79% considered that hydrography is going through at least a very important period of change – only 4% thought it was *business as usual*.

⇒ 99% indicated that training should be adapted to rapid technological changes; only 1% thought that hydrography will be same.

⇒ 99% believed that hydrography is impacted by artificial intelligence.

⇒ 87% saw that in the future, hydrographers will invest much more time in managing data quality from multi-sources; whereas only 11% expected the bulk of their activity would be in field surveys.

⇒ 91% saw that in the future, data will come mostly from crowd-sourced bathymetry, satellite-derived bathymetry and autonomous platforms. 9% indicated that it would come from Hydrographic Offices (HOs).

⇒ 58% agreed with adopting the word "hydrospatial", either the IHO or by those HOs willing to do so. 42% did not agree to adopt the new word.

6. Conclusion

The objective and intention of this session were fulfilled. Not only did it generate a lot of discussion before and during the session, but there was also much more afterwards. It is remarkable to notice that the vast majority is engaged and mobilized towards this hydrospatial revolution. Hopefully, this article and others to come will continue to raise the issue and encourage the use of the word "hydrospatial!"

Traditional hydrography as we know it, both in the past and for the future, is essential; however, moving towards greater use of the word "hydrospatial" can not only highlight the traditional benefits and role of hydrography but will at the same time emphasize the new roles for our hydrographic geospatial data and our expertise in an exciting, modern and inspirational way.

Feedback, comments and suggestions are welcome, and expected or to join the "Hydrospatial Activists Club & Community" do not hesitate to contact: dhains@h2i.ca or write on: www.h2i.ca

7. Acknowledgments

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Ponce, R. *Senior Executive Consultant-Maritime Services at Esri-Article Reviewer.*

Sanfaçon, R. *President Canadian Hydrographic Association (CHA)-Supported the organization of the 1st VIP Panel Session at the CHC 2020.*

* One anonymous*, Experienced Hydrographic Professional-Article Reviewer.*

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Notes

IMPACT OF CYCLONE IDAI ON THE HYDROGRAPIC SERVICES THE CASE OF MOZAMBIQUE

By S. Canhanga, S. Munguambe, H. Chavango and E. Macia
(INAHINA - National Institute for Hydrography and Navigation)
E-mail: scanhanga@inahina.gov.mz

1. Abstract

The deadliest tropical cyclone in 2019 was the Intense Tropical Cyclone Idai in the South-West Indian Ocean, which killed over 1,303 people in Mozambique, Malawi, Zimbabwe, and Madagascar. In this study, the impacts of cyclone Idai on the Mozambican Hydrographic Services is presented. The study has identified the need to settle an appropriate Disaster Risk and Management System in National Hydrographic Services, as well as, the need to strengthen the capacity of the National Hydrographic Services to respond to natural disasters and develop standard operating procedures where the support from international community may be of paramount importance.

2. Introduction

According to the English Wikipedia (2019), a tropical cyclone is a rapid rotating storm system characterized by a low-pressure center, a closed low-level atmospheric circulation, a spiral arrangement of thunderstorms that produce heavy rain , and strong winds, that in ocean may generate waves of high heights.

Tropical cyclones in 2019 were spread out across seven different areas called basins. During 2019, 143 systems were formed. 43 tropical cyclones have been named by either a Regional Specialized Meteorological Center (RSMC) or a Tropical Cyclone Warning Center (TCWC). The deadliest tropical cyclone of the year was the Intense Tropical Cyclone Idai in the South-West Indian Ocean, which killed over 1,303 people in Mozambique, Malawi, Zimbabwe, and Madagascar, and caused more than $2.001 billion in damages.

In Mozambique, the impact of tropical cyclone Idai was catastrophic in and around Beira City, where it caused the deaths of more than 600 people. An estimated 1600 people were injured and approximately 1.8 million people were affected. The World Bank's rapid assessment made in April 2019, estimated USD 773 million in damages to buildings, infrastructure and agriculture, and a more elaborated evaluation on the donor conference for infrastructure reconstruction have estimated USD 3.2 billion as the cost for reconstruction post-cyclone Idai in Mozambique.

3. Event Characterization

Tropical Cyclone Idai started to develop on 4th March close to the coastline of the province of Zambézia as a tropical depression with wind speeds of about 55 km/h gusting up to 75 Km/h (WMO, 2019). The system made a first landfall on the same day, north of Quelimane. During the following 4 days, a remnant of low pressure persisted over land while the system headed north and then northwestward until the 6 March, before turning back east-southeastward early on 7 March close to the Mozambique-Malawi border. From 6 to 8 March persistent local and heavy rainfall with associated thunderstorms affected southern Malawi and the provinces of Zambézia, Sofala, Nampula, Tete and Niassa (rainfall amounts in excess of 400 mm were recorded at some INAM's weather stations in Ulongue, Tsangamo, Mocuba). This caused a rise in water to above alert levels in the basins of Licungo, Raraga, Namacurra, Zambeze and in the sub-basin Revubuè. Resulting floods occurred in the lower Licungo and in the city of Tete

On 9 March, the remnant low pressure moved back towards the sea to the Mozambique Channel. At sea, it intensified rapidly maturing into an intense tropical cyclone with winds gusting up to 250 km/h by 11 March, off the western coast of Madagascar.

Idai (***Figure 1***) started to reverse its track early on the 11th towards the Mozambican coastline, as anticipated many days before by numerical weather prediction models. Since the 6th of March, this reversing track was well suggested by the European ensemble forecast with a possible threat of a mature tropical cyclone for central Mozambique. On 12 March, track forecast uncertainty had reduced and was well below usual standards, clearly indicating that Idai would hit the Beira area. Landfall eventually occurred on the evening of the 14th, around 2200UTC, in the northern vicinity of Beira as an intense tropical cyclone based on the South-West Indian Ocean Basin terminology that corresponds to category 4 (out of 5) on the scale used in Mozambique. At its landfall, Idai's winds estimated by the Regional Specialized Meteorological Centre (RSMC) La Réunion were blowing at 165 km/h and gusting up to 230 km/h (real time analysis) bringing torrential rains and seas waves with very high heights likely exceeding 10 meters (WMO, 2019).

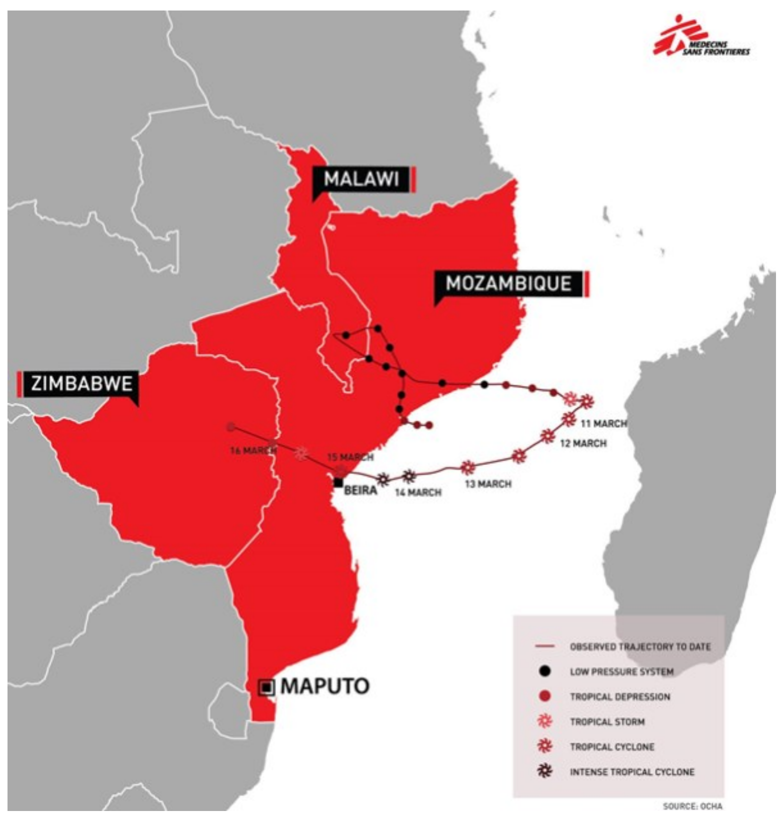

Figure 1: *Track and intensity of Tropical Cyclone Idai, from 4 to 16 March 2019. (**Source: Doctors without borders)***

From 15th March, Tropical Cyclone Idai started to weaken as it moved inland. Associated heavy rainfall spread over Central Mozambique going inland up to eastern and central parts of Zimbabwe. This, combined with the river flows from upstream countries, fed the major and deadly flood event, mainly in the Búzi and Púnguè Rivers basins that started a few days (3 to 4 days) after the cyclone passed over Beira. The city of Beira and its peripheries, recorded moderate floods. In the same period the Save river basin recorded high water flows as a result of water coming from upstream, yet without significant impacts. The Dams of Cahora Bassa and Chicamba had an increase of volume of storage to nearly 99% and 76%, respectively.

4. Objectives of the paper and its alinment with National and International policies and strategies

The two main objectives of this paper are:

- Highlight the impacts of tropical cyclone Idai on the Mozambican Hydrographic Services;
- Emphasize and describe the identified needs to bring the National Hydrographic Services and Institutes back to the baseline of International Hydrographic Organization (IHO) standards after the occurrence of Tropical Cyclones.

Reaching the proposed objectives would create a basis for any future international (IHO, SAIHC, or at bilaterally) intervention, which should aim at enhancing the response capacity of the National Hydrographic Services in developing countries, in times following extreme weather or climate events.

Those objectives are seen as aligned with the visionary aspirations of SAIHC and IHO, very well enshrined in the IHO strategy, objectives and vision, especially on what concerns to:

- Assist MS to achieve sustainable development and improvement in their activities to meet hydrographic, cartographic and marine safety obligations, with particular reference to recommendations in SOLAS, and other international instruments – As per IHO capacity building strategy/policy paper (IHO, 2014).
- Create a global environment in which states provide adequate, standardized and timely hydrographic data products and services – As per IHO vision.
- Enhance cooperation on hydrographic activities among states on a regional basis – As per IHO Objectives;
- Support national initiatives aimed at obtaining better hydrographic information – As per IHO strategic directions (IHO, 2017)

5. Importance of Beira Port to the Country and the Region

Besides the importance of Beira Port to Mozambique, as it is the second most important port of the country, it also constitutes one of the infrastructures within the Beira corridor. Beira corridor (***Figure 2***), has been in existence for more than a century, since 1889 as a gateway to Zambia, Zimbabwe and Malawi's export to the rest of the world (SundayMail, 2016). From a couple of years ago onwards, the corridor has also been serving the export/import of goods from/to DRC.

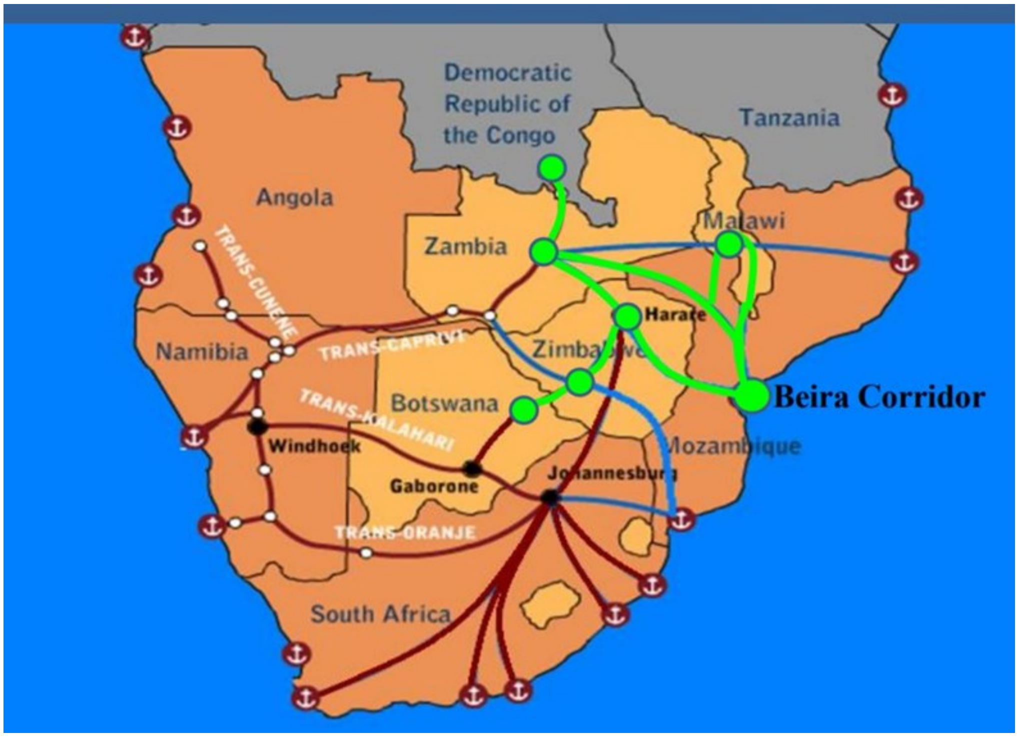

Figure 2: *Beira Corridor. Lines in green represents the corridor's routes, and the corresponding countries that the corridor can serve. (Sunday Mail, 2016)*

Using Beira Port presents also an opportunity to DRC, Malawi, Zambia and Zimbabwe to decongest the North-South Corridor, while ensuring the efficient and cost effective moving of goods, as per the information contained in ***table 1***.

Table 1: Main Ports VS Main Cites in Land Locked Countries, and the corresponding distances.

	Cities	Harare Zimbabwe	Bulawayo Zimbabwe	Lusaka Zambia	Kitwe Zambia	Lubumbashi DRC	Blantyre Malawi	Lilongwe Malawi
Ports		**Distances in Km**						
Beira		550	726	1054	1370	1600	812	950
Durban		1711	1454	2380	2707	2611	2323	2678
Dar-es-Salam		2634	3028	1985	1951	2290	2031	1667

Therefore, apart from the immensurable benefits that the Beira Port brings to Mozambique, there is a need to fully explore the enormous opportunities that Beira Port can offer to those four Land locked countries as those countries (Zambia, Zimbabwe, DRC, and Malawi) seek for competitiveness of their products and exports.

6. Effect of cyclone IDAI on the Hydrographic Services in Mozambique

An emergency meeting was held at INAHINA – Instituto Nacional de Hidrografia e Navegação – (National Institute for Hydrography and Navigation) on 15th of March, aiming to identify immediate measures to be taken to mitigate the possible effects of cyclone Idai, in Beira harbor. Among other measures, the meeting identified the creation of a commission to deal with the impacts of the cyclone to INAHINA as well as, to the Beira Port, and the mitigation measures, which would allow continuation of usage of Beira Harbor, as well as the continuation of provision of hydrographic services by INAHINA. Due to the lack of communication, and the impossibility to access Beira, the mission could travel to Beira only on 17th of March.

While in Beira, the mission identified a massive devastation/destruction, and a number of challenges impairing a conducive environment to ensure the delivering of Hydrographic Services for those demanding the Beira Harbor. The mission then proposed measures to address the identified destruction. A summary of the identified destructions, challenges, as well as, the proposed measures, are presented below:

⇒ Effects on the hydrographic assets

Location of the missed hydrographic boat (Lago Niassa)

The Hydrographic boat *Lago Niassa* with all hydrographic equipment installed, drifted during the passage of the tropical cyclone Idai, and was found aground near the mouth of Buzi River, at a distance of approximately 10.0 Km from the quay/pier where it was docked. With assistance of a Vessel from the Fishery Office, the hydrographic boat was retrieved and brought back to the pier/ quay. The mission assessed the vessel conditions, and the main findings were:

- The access door to the cabin broken
- Several breaches on the boat
- Failures of the starboard engine
- Damage to some of the hydrographic survey hardware

Figure 3 illustrates the damages suffered on the hydrographic boat *Lago Niassa*, upon the passage of cyclone Idai.

Figure 3: *Damages from Cyclone Idai on the hydrographic survey boat. On the left side can be seen the breaches in the boat.*

Due to the significance of the damages identified, the lack of capacity to repair the boat locally, the need to have this unit in Beira to support the maintenance of the Buoys along the Beira ac-

cess Channel, the boat was sent afterwards to one shipyard in Maputo, for restoration. The costs associated with restoration, as well as the mobilization costs of the boat to the Maputo Shipyard, was estimated at USD 40.000 (INAHINA, 2019).

The computer system of the Hydrographic Services, namely computers, printers, and servers, were also severely affected by the cyclone, as all them were submerged into water. The cost estimate to recovery the computer system corresponds to approximately to USD 18.000.

⇒ **Effects on the aids to navigation**

Location of the missed Buoy Tender (Beacon Ship) - Bazaruto

INAHINA maintains a Buoy Tender, *Bazaruto*, 52.3 meters length 11.2 meters beam, and 3.5 meters draft. Due to the very intense winds of approximately 230 Km/h, and higher wave heights likely exceeding 10 meters, the vessel crew withdrew from the vessel after starting the breaking of the vessel's mooring lines. The vessel drifted during the night running aground into mangroves, at a distance of approximately 2.5 Km from the quay. The mission assessed the vessel conditions, and the main findings were:

- A breach in the collision-tank
- A tear on the bow

Figures 4 below illustrate the damages suffered on the Buoy Tender *Bazaruto*, upon the passage of cyclone Idai.

Figures 4: *Illustration of the Buoy Tender Bazaruto grounded approximately 2 Km from the quay.*

After small technical intervention made by INAHINA, in collaboration with the other National companies, the vessel was finally rescued from it grounded position and docked again in the Beira quay/pier. The rescue operation was made by contracting a South Africa company, at a cost of approximately USD 45,000, and currently the Vessel is still docked for restoration. These interventions may cost approximately USD 100,000.

Assessment of the buoys along the Beira Port access channel

With assistance from Port and Railway company in Beira, all the drifted buoys (three in all), were repositioned. Buoy Alpha was damaged and was removed as its tower needed to be repaired. Afterwards, there was a need to hire a tender vessel (as the existing tender vessel were affected with the cyclone) for the replacement of the Buoy. The estimated costs to carry out this activity is evaluated at USD 136,000

Assessment of the Beira Lighthouse (Macuti Lighthouse)

Findings in the lighthouse were as the followings:

- The protection wall was completely destroyed
- The sand material around the lighthouse had moved, exposing the underlying lighthouse structure to saltwater, and leaving the steps to access the lighthouse at risk of collapse.

Figures 5 below show the damages suffered on lighthouse, upon the passage of cyclone

Idai.

The mission identified a consulting company to assess the damages and come up with a technical and financial proposal to restore the lighthouse. The restoration includes building of a structure for coastal protection. The restoration costs of the lighthouse, including the technical study, is estimated at USD 750 000

Figure 5: *Illustration of the lighthouse damages upon the passage of cyclone Idai. It can be seen from the picture the removal of sand material, as well as the risky of collapsing the steps that provide access to the lighthouse*

⇒ ***Effects on the INAHINA's Office in Beira***

The cyclone Idai has caused:

- The removal of the roof of the INAHINA's office in Beira
- Destruction of all the furniture
- All the computer equipment was damaged due to rain and saltwater intrusion into the office
- All the documents and archives were wet as result of water entering into the offices

Figures 6 below illustrate the status of the INAHINA's office, upon the passage of cyclone Idai.

Figures 6: *Illustration of the INAHINA's Office upon the occurrence of cyclone Idai. From the figure it is possible to see the damages on the computer equipment, ceil, and furniture.*

The estimated costs for recovering activities of the INAHINA's office in Beira is estimated to be approximately USD 120000.

⇒ **Identified challenges post cyclone**

Upon the occurrence of the cyclone, INAHINA was called to carry out a hydrographic survey along the Beira access channel to verify if a container from the Beira Port, reported missing after passage of Cyclone Idai, was obstructing the access channel. Resorting to Side Scan Sonar, INAHINA has surveyed the channel, and identified no container along the channel. This activity was carried out at cost of USD 20.000

Another issue worthy of attention is the fact that, in 2018, INAHINA surveyed Beira Port Channel and its adjacent areas to update the Beira Port Approach and Beira Port Nautical charts. Upon the occurrence of the cyclone, which brought waves of almost 10 meters in height, it is suspected that the morphology of Beira Bay has undergone substantial modifications that would make it unsafe to produce an unlimited edition of Beira Charts based on the hydrographic data collected before the cyclone Idai.

In November 2019, INAHINA finally conducted a hydrographic survey with a single beam echo sounder, which was used to survey the adjacent areas of the channel, and a multibeam echo sounder, used to survey the Beira Port access channel. The total costs to this mission, corresponded to approximately USD 250.000,00.

7. Recommendations and Conclusion

Mozambique is the fifth most vulnerable country in the world to the natural disasters. According to MITADER (2016), the country is vulnerable to Sea Level Rise, Drought, Tropical Cyclones, and Floods. In 2019, Tropical Cyclone Idai severely affected the Sofala Province, where the Beira Port, the second major port of the country, is located. Beira Port not only benefits Mozambique but is also of paramount importance to land-locked countries, such as Malawi, Zambia, Zimbabwe, and Swaziland, as well as, to the others countries, like the Democratic Republic of Congo, as this port serves as a gateway for export/import of goods.

The Hydrographic Services of Mozambique were also harshly affected by the cyclone, particularly the infrastructure, hydrographic survey equipment, as well as on the Tender vessel, and Aid to Navigation system (Buoys). The total costs to recover the affected hydrographic services was estimated at more than USD 1,859,000, which corresponds to a substantial part of the INAHINA's annual budget.

Almost all the infrastructure damaged, including the hydrographic survey vessel, were needed immediately following the cyclone. Hydrographic efforts were required for disaster recovery, not only to serve Mozambique country, but also the region as mentioned above.

The budget constraints faced by Mozambique, combined with the country's vulnerability to natural disasters, is at odds with the country's obligation to continuously provide Marine Safety Information to the users of Sea, and the role of the Beira Port to supply the country and the region. This cyclone exposed the Hydrographic Services in Mozambique to a set of challenges that leads us to recommend the following:

- The need to request support from IHO and other international institutions to define an appropriate Disaster Risk Monitoring and Management System in National Hydrographic

Services, to mitigate the impacts of Natural disasters, in such events like Tropical Cyclone Idai.

- The need to strengthen the capacity of INAHINA to respond to natural disasters and develop standard operating procedures where the support from international community may be of paramount importance.

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WMO Mission Report Following Tropical Cyclone IDAI

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General Information

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General Information

OBITUARY

FOR DR. SALEM MASRY

Dr. Salem Masry, the founder of what is now Teledyne-CARIS, passed away on February 1, 2020 in Fredericton, New Brunswick, Canada after a long battle with Parkinson's disease and its complications. He was 81 years old.

Salem was born in Asyut, Egypt, a city of Coptic Christians. He earned a Bachelor Science degree in Civil Engineering, then a PhD in photogrammetry from University College London, before becoming one of the founding members of the Department of Surveying Engineering at the University of New Brunswick in 1966. Salem's students at UNB remember him as loyal, patient, calm, with a strong work ethic.

Salem was a pioneer in the field of digital mapping and founded a company in 1979 to commercialize the results of his research, which he called Universal Systems (eventually CARIS and now Teledyne-CARIS). CARIS grew to be the leading company in ocean mapping and hydrographic charting software. Dr. Masry personally interviewed each potential new employee, who all remember him for his compassion, intelligence, work ethic, amazing memory and quick-witted sense of humor. He touched many lives with his bright spirit and will be greatly missed.

The Canadian Hydrographic Association has established a biennial CHA-Sam Masry Award, to be awarded to an individual at future Canadian Hydrographic Conferences who has contributed significantly to the Hydrographic Industry in Canada and Internationally. Two indicators of the success of Sam Masry's vision for hydrographic processing software are:

In the entrance atrium to the Valparaíso headquarters of Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA) are four clocks, each on one of the four walls. Three of these clocks keep time in world capitals (Washington, London, Monaco). The fourth clock keeps time in Fredericton, New Brunswick, where CARIS is located.

In September 1999 at an IHO workshop in Trieste on "Modern Management of a Hydrographic Service", in response to a question about standardization, Captain Robert Ward from Australia said to the assembly "The most important influence for international hydrographic standardization is the widespread adoption of CARIS software by IHO Member States."