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Evaluation of Port Prosperity Based on High Spatial Resolution Satellite Remote Sensing Images

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Abstract: More and more ports appeared along China's coastline, which destroyed natural coastline and coastal landscape. Some of them are inefficiency operations. It is important to evaluate operational efficiency of ports to reveal their position in regional competitive environment. In this study, high spatial resolution satellite remote sensing images were used to monitor ship number and plane area. The port-use prosperity index (PUI) was subsequently proposed to quantitatively describe port-use business and reveal port-use efficiency. The PUI was applied to six ports around the Bohai Sea, China. The number, scale, and plane of ships docked in these ports were easily monitored by the high spatial resolution satellite remote sensing images, and the PUI was calculated using a ship's total plane area and length of docked coastline. The PUI is an objective and practical index for evaluating port-use efficiency. It can be used to compare differences in port use and indicate temporal port-use dynamics. The PUI values of Jingtang and Tianjin Ports were the highest (17.75 and 14.14, respectively), whereas that of Yantai Port was the lowest (8.31). The PUI values of the remaining ports were 9.0–10.70. A linear relationship existed between port throughput and PUI in the studied ports. This can forecast port throughput by monitoring and calculating PUI based on high spatial resolution satellite remote sensing images.

Keywords: port-use prosperity index (PUI); ship number; plane area; port-use efficiency; the Bohai Sea

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1 Introduction

With the continuous advancement of global economic integration and the constant transition of inland economies towards sea-oriented economies, more and more ports have been constructed along coastline, especially in China (Zhang et al., 2011). There are seven of world's top ten ports in China. Hence, ports are becoming essential basic support platforms for many coastal cities to develop an outward-oriented economy and strengthen their trading (Yang et al., 2011). As early as 1980s, port efficiency has been attracted by some studies (De Monie, 1987; Bendall and Stern, 1987). An important indicator of port's operational performance is cargo throughput. It is defined as the total amount of cargo handling through a port over a certain period (year, quarter, or month) (Huang et al., 2003).

Extensive studies have been conducted in port use efficiency (Liu, 1995; Tongzon, 1995; Sachish, 1996). In general, the traditional methods to evaluate port use efficiency include parametric and nonparametric methods (Chen, 2019). Although parametric methods enriched the index system of port efficiency evaluation, it is subjective in function setting and data selection (Coto-Millan et al., 2000; Cullinane et al., 2002; Clark, 2004; Blonigen and Wilson, 2006). By comparison, the

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nonparametric methods, such as Data Envelopment Analysis (DEA), are advantageous in solution with multi-index input and output (AL-Eraqia et al., 2008; Chudasama and Pandya, 2008; Dayananda and Dwarakish, 2018). However, Most existing researches focused on index or model with data coming from port statistical reports, and most port operational data are inaccessible or released slowly and limited, they could not meet the demand of port efficient evaluation.

High-resolution satellite remote sensing technology has been developing rapidly since the beginning of the 21st century. It has been widely used to monitor and research resource environments, human activities, and disaster assessment, serving as the primary means of global earth surface observation. China's high-resolution Earth Observation System key special project and its operational application in various economic sectors, as well as research and development in the application of data from domestic resource and mapping satellites, have gradually formed an earth observation system with high spatial, time, and hyperspectral resolution (Yang et al., 2017). High spatial resolution satellite remote sensing images provide reliable data sources and feasible technical approaches for monitoring ships in ports. Hu et al. (2009) established an in-port ship detection method based on local self-similarity in remote sensing images. Zhang et al. (2017) employed a visual saliency model to extract ship targets with different gray levels in high spatial resolution satellite remote sensing images and applied the multi-feature synthesis method to eliminate false targets. Zhang et al. (2017) also established a sea-surface ship detection algorithm based on high-resolution optical remote sensing images. Wu et al. (2018) established an in-port ship detection method based on bow feature extraction and contour positioning. The scale and number of cargo ships docked in a port within a certain period of time can represent the port cargo throughput. There are few studies on port use efficiency by remote sensing images.

Focusing on port-use efficiency, this study created a port-use prosperity index (PUI), based on the number and scale of cargo ships docked in ports, that can be monitored using satellite images. Six ports around the Bohai Sea in China were selected as test areas to explore the application of PUI. In this study, we analyzed: 1) high-resolution remote sensing images of docked cargo ships to determine the significance of different ships to port utilization. 2) PUI dynamics of the six ports in five time periods, and 3) correlations between PUI and cargo throughput. The aim of this paper is to propose an evaluation index for port efficiency based on high resolution remote sensing images, and provide fast and practical method for port operation analysis, export-oriented economic monitoring.

2 Materials and Methods

2.1 Study area

Six ports around the Bohai Sea, China (Fig. 1), namely Bayuquan, Jinzhou, Longkou, Yantai, Jingtang, and Tianjin Ports were selected to test effectiveness and practicability of PUI proposed in this paper. Bayuquan Port is located in Yingkou City, Liaoning Province. It is the nearest port to northeastern China and eastern Inner Mongolia. Its land and water area is 5690.61 ha, and it has a quay length of 24 km. Jinzhou Port is located in the Jinzhou City, Liaoning Province, and is the only port for the export of coal resources in Inner Mongolia. It has a land and water area of 4346.56 ha and a quay length of 9.20 km. Longkou Port is located in Yantai City, Shandong Province, and is a major logistics hub in the western Shandong Peninsula. It has a land and water area of 939.97 ha and a quay length of 9.80 km. Yantai Port is located in Yantai City, Shandong Province, and is the main logistics hub in the northern Shandong Peninsula. It has a land and water area of 1000.26 ha and a quay length of 13.20 km. Jingtang Port is located in the Tangshan City in Hebei Province and is a major logistics hub for Beijing and the northern Hebei Province. Its land and water area is 2703.09 ha, and its quay length is 12.70 km. Tianjin Port is located in the Tianjin Binhai New Area and is the maritime gateway of the Beijing-Tianjin-Hebei region, serving as the eastern starting point of the China-Mongolia-Russia Economic Corridor, an important node of the New Asia-Europe Continental Bridge and the strategic fulcrum of the 21st Century Maritime Silk Road. This port has a land and water area of 15451.70 ha and a quay length of 42.50 km. Among these six ports, Tianjin Port is a super-large port. Bayuquan Port and Jingtang Ports are large ports. Longkou Port and Yantai Ports are large to medium ports, while Jinzhou Port is a medium port.

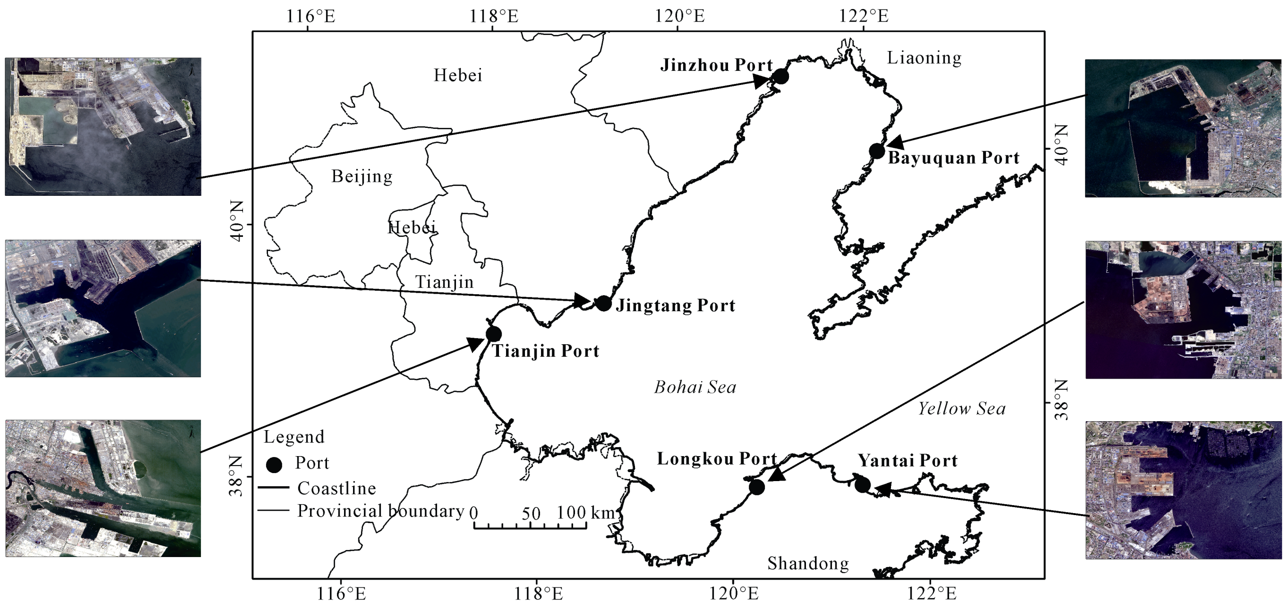

Fig. 1 Location of six test ports around the Bohai Sea

2.2 Data and processing

The docking status of cargo ships in the six ports were monitored using high-resolution remote sensing images acquired by the Tianhui-1, Ziyuan-3, Gaofen-1,and Gaofen-2 Satellites, with a spatial resolution of 2.0 m or 2.1 m (Table 1). For each port, five images from 2013–2017 were randomly selected as the basic data sources for monitoring the docking status of in-port ships. The five images selected randomly are equivalent to five random samples in each port. The port cargo throughput data come from *China Port Yearbook* of each port (China Port Association, 2013–2017).

Table 1 Images information for port prosperity monitoring of six ports around the Bohai Sea

Port name	Monitoring number	Image source	Image acquisition time (year/month/day)	Image spatial resolution (m)
Bayuquan Port	1	TH-1	2013/04/03	2.00
	2	ZY-3	2014/06/15	2.10
	3	GF-1	2015/03/24	2.00
	4	ZY-3	2015/04/15	2.10
	5	GF-1	2016/08/22	2.00
Jinzhou Port	1	TH-1	2013/09/27	2.00
	2	ZY-3	2013/11/29	2.10
	3	GF-1	2016/06/07	2.00
	4	GF-1	2016/07/27	2.00
	5	ZY-3	2016/08/26	2.10
Longkou Port	1	GF-1	2014/05/03	2.00
	2	ZY-3	2015/10/12	2.10
	3	ZY-3	2016/01/11	2.10
	4	GF-1	2016/06/17	2.00
	5	GF-1	2017/03/11	2.00
Yantai Port	1	GF-1	2015/07/21	2.00
	2	ZY-3	2016/06/01	2.10
	3	GF-1	2016/06/25	2.00
	4	GF-1	2016/08/16	2.00
	5	GF-1	2016/11/17	2.10

Continued table

Port name	Monitoring number	Image source	Image acquisition time (year/month/day)	Image spatial resolution (m)
Jingtang Port	1	GF-1	2013/11/17	2.00
	2	GF-1	2014/10/16	2.00
	3	GF-1	2015/07/05	2.00
	4	GF-2	2016/06/25	2.00
	5	GF-2	2017/02/11	2.00
Tianjin Port	1	GF-1	2013/05/01	2.00
	2	ZY-3	2015/02/14	2.10
	3	GF-1	2015/06/16	2.00
	4	GF-1	2016/05/13	2.00
	5	ZY-3	2017/04/07	2.10

Notes: GF-1: Gaofen-1 Satellite; GF-2: Gaofen-2 Satellite; TH-1: Tianhui-1 Satellite; ZY-3: Ziyuan-3 Satellite

Image processing mainly involved geometric correction, image graying, and image enhancement. Image graying is a process of equalizing the red, green, and blue bands in each pixel of a true-color composite to reveal image features of port and ships. A weighted average method was adopted in this study to calculate gray value of the red band, green band and blue band of each image based on the following equation:

$$Gray_{(i,j)} = 0.30R_{(i,j)} + 0.59G_{(i,j)} + 0.11B_{(i,j)} \quad (1)$$

where $Gray_{(i,j)}$ is the gray value of pixel in row i, column j. $R_{(i,j)}$, $G_{(i,j)}$ and $B_{(i,j)}$ is the gray value of the red band, green band and blue band in row i, column j. The weights of the red band, green band, and blue band were obtained from Zhang et al. (2006). After the calculation of the weighted average gray values, grayscale images of the ports were obtained and taking Bayuquan Port as an example (Fig. 2).

Image enhancement was performed using a piecewise linear stretch algorithm that could enhance the region of interested and fully display the internal information of an image (Zhou et al., 2009). The image enhancement effect of piecewise linear stretch in Bayuquan Port is illustrated in Fig. 3.

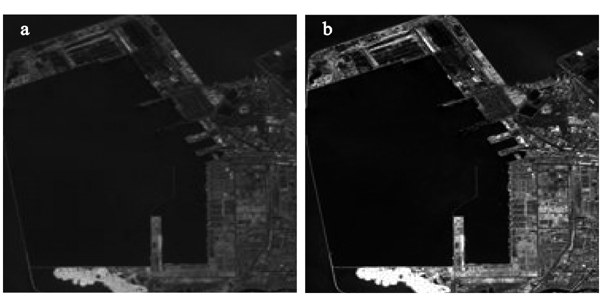

Fig. 2 Result of image graying for Bayuquan Port: (a) original port image and (b) grayscale image

Fig. 3 Enhanced image of Bayuquan Port using piecewise linear stretch algorithm

2.3 Information extraction of cargo ships in ports

2.3.1 Feature analysis of cargo ships from remote sensing images

Cargo ships in ports mainly included container ships, bulk carriers, oil carriers, and ore ships. Image identification of a ship target was generally based on the size, appearance, and shape of the ship, the gray values of its image, and the docking location. The dimensional characteristics of the ship mainly included its length, width, and plane area. Most docked ships in the ports had a length of 20–320 m, and their width mostly ranged from 5 to 70 m. As the size of a ship depends the shipyard's manufacturing process, ship model, and owner country, ship targets may differ dramatically in size, necessitating the additional consideration of the plane shape characteristics when determining whether an imaged object in a port is a cargo ship. Generally, the plane shapes of cargo ships were mostly oval, consisting of parallel and straight hull sides with an oval-shaped bow and stern. Oil carriers and container ships were not much different from cargo ships. Grayscale features provide another criterion of ships docked in a port (Zhang and Jin, 2006). As the reflectance of ships differ significantly from that of the port water surface, the images of ships and water surface differ significantly in grayscale values. In addition, in terms of positional characteristics, cargo ships are usually docked at wharf, with the ship's main axis parallel to the wharf line.

2.3.2 Information extraction of ships based on grayscale histogram

A grayscale histogram presents the statistical distribution of pixel values in a remote sensing image. Commonly used threshold selection methods are based on these grayscale histograms. When selecting the value at the valley bottom in a bimodal grayscale histogram as the threshold, the ship targets to be extracted can be separated from the sea background. Generally, the valley bottom grayscale values are selected using the minimum or optimal threshold methods (Ge et al., 2018). Analyses of 30 images of the Bohai Sea ports revealed that the port area images usually showed a bimodal pattern in the grayscale histograms. Therefore, an iterative optimal threshold method can be used to perform threshold segmentation on port images.

In addition, due to ship superstructures, shadows are often formed near the ship mast, chimney, and other structures in optical images. In image segmentation, the shaded parts are often mistakenly classified as background due to their low grayscale values, which results in gaps and holes in the segmented ship target (Kapur et al., 1985; Serkan et al., 2015). To obtain a complete and accurate cargo ship target, appropriate correction needs to be performed on the threshold-segmented image. To this end, the corrosion, expansion, opening, and closing algorithms in mathematical morphology as well as the sweep-line algorithm in computer graphics are usually adopted to correct the missing parts of ship targets (Liu and Guo, 2013; Deng and Huang, 2017). For example, an in-port ship image was extracted using the iterative optimal threshold method and corrected for missing parts using the sweep-line algorithm (Fig. 4).

After the segmentation, extraction, and correction of the images of in-port ship targets, binarization and statistical analyses were performed to calculate the plane area of a docked ship through the ship's grid pixels. Setting the image grayscale value of the background water surface in a port to 0 and the image grayscale value of ship targetsto1,the plane area S of the ships docked in the port could be calculated as follows:

$$S = \sum_{j=1}^{n} \sum_{i=1}^{m} p(i, j) \quad (2)$$

where S is the plane area (m^2) of the docked ships in the port, $p(i, j)$ represents pixel with grayscale value of '1' after binarization, with m representing rows and n for the columns.

2.4 Prosperity assessment of port utilization

In general, a larger number of ships docked in a port with a larger ship scale will lead to a larger total ship plane area. The larger the total plane area of docked ships in a port, the busier the port, the higher the port-use efficiency, and the higher the prosperity of hinterland economic development. To quantitatively describe port-use efficiency, a port-use prosperity index (PUI) was proposed to reflect the degree to which a port is being used. This index is defined as the ratio of the total plane area of in-port docked ships to the total length of coastline:

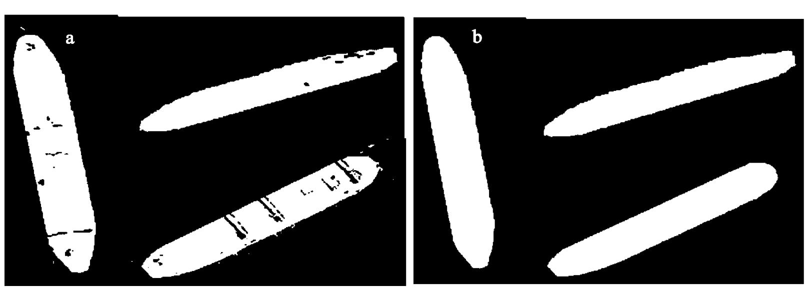

Fig. 4 Ship extraction and replenishment from remote sensing images: (a) ship extraction based on iterative optimal threshold method and (b) ship replenishment based on scan line algorithm

$$PUI = \frac{\sum_{i=1}^{n} a_i}{L} \quad (3)$$

where a_i represents the plane area (m^2) of cargo ship i docked along the coastline, n represents the total number of cargo ships, and L represents the length (m) of coastline in a port. When statistically calculating the area of docked ships in a port, idle ships that have been docked in the port for a long time as well as docked non-cargo ships used for port maintenance and management should be excluded.

3 Results

3.1 Docked ship characteristics in six ports around the Bohai Sea

Docked cargo ships were extracted for the six ports around the Bohai Sea using high spatial resolution remote sensing images. The number, size, and plane areas of ships docked in each port at different time points were statistically counted. Remote-sensing monitoring and in situ identification of ships in the six ports revealed that large ships with a displacement of more than 10 000 t usually had a plane area more than 10 000 m^2, whereas medium-sized ships with a displacement of 5000–10 000 t generally had a plane area of 5000–10 000 m^2.

The docked cargo ships statistic dynamic of six ports is shown in Table 2. Tianjin Port is a super-large port with the largest number of docked cargo ships, which was relatively stable at an average of 70 for each monitoring time point. Its average total plane area of docked cargo ships was 22.57 × 10^4 m^2. Overall, large cargo ships accounted for 29.55% of all ships, whereas medium cargo ships accounted for 69.03%. Bayuquan and Jingtang Ports are both large ports. Bayuquan Port had an average of 39 docked cargo ships, with a maximum of 56 and minimum of 23, indicating substantial fluctuation. Its average total plane area of docked cargo ships was 23.57 × 10^4 m^2, with large cargo ships accounting for 20.41% of all ships. For Jingtang Port, the average number of cargo ships was 31, with a maximum of 40 and minimum of 18. Its average total plane area of docked cargo ships was 22.57 × 10^4 m^2, with large cargo ships accounting for 38.56% of all ships. Longkou and Yantai Ports are large to medium ports, with an average of 20 and 22 docked cargo ships, respectively. Their docked cargo ships had a total plane area of 9.80 × 10^4 and 11.02 × 10^4 m^2, respectively. Jinzhou Port is a medium port, with a relatively small number of docked cargo ships, fluctuating from 6 to 16, with an average of 12. Its average total plane area of docked cargo ships was 8.51 × 10^4 m^2, with large cargo ships accounting for 35.48% of all ships.

Table 2 Cargo ship statistics in six ports around the Bohai Sea

Port name	Monitoring time	Total plane area (m^2)	Total number of ships	Number of large ships	Number of medium ships
Bayuquan Port	2013/04/03	176272.06	24	4	18
	2014/06/15	194345.44	23	7	15
	2015/03/24	275508.67	56	12	23
	2015/04/15	218097.07	44	10	18
	2016/08/22	314470.00	49	7	17
Jinzhou Port	2013/09/27	79784.62	11	4	7
	2013/11/29	53951.16	6	2	4
	2016/06/07	90212.04	14	6	8
	2016/07/27	106775.50	16	7	9
	2016/08/26	94569.21	15	3	7
Longkou Port	2014/05/03	78918.58	15	3	5
	2015/10/12	58870.27	22	1	3
	2016/01/11	136494.97	27	7	11
	2016/06/17	120241.12	19	5	9
	2017/03/11	95466.46	18	4	6

Continued table

Port name	Monitoring time	Total plane area (m^2)	Total number of ships	Number of large ships	Number of medium ships
Yantai Port	2015/07/21	115276.99	19	3	9
	2016/06/01	94327.04	19	0	8
	2016/06/25	117505.30	25	5	20
	2016/08/16	145140.20	32	4	14
	2016/11/17	78873.73	13	2	8
Jingtang Port	2013/11/17	180922.22	30	7	12
	2014/10/16	238563.41	34	9	17
	2015/07/05	201007.37	18	18	0
	2016/06/25	246010.47	31	13	18
	2017/02/11	261872.98	40	12	20
Tianjin Port	2013/05/01	442131.44	70	20	50
	2015/02/14	698580.92	65	19	45
	2015/06/16	676696.65	71	21	50
	2016/05/13	584110.01	72	20	52
	2017/04/07	606692.87	74	24	46

3.2 PUI in six ports around the Bohai Sea

The PUI was calculated for each port at different monitoring times (Table 3). Jingtang Port had the highest average PUI value (17.75), indicating that this port had the highest port-use efficiency and its hinterland had the most prosperous outward-oriented economy. Tianjin Port had the second-highest average PUI (14.14), demonstrating a relatively high use efficiency. The high PUIs of Jingtang and Tianjin ports indicated that the Beijing-Tianjin-Hebei region, and the hinterland shared by both, had the most prosperous outward-oriented economy. The maximum PUI of Yantai Port was 10.95 and the minimum was 5.95, with an average of 8.31. This shows that Yantai Port had the lowest use efficiency, representing the hinterland with the least prosperous outward-oriented economy. Bayuquan Port, Jinzhou, and Longkou Ports had similar PUI values, ranging from 9.22 to 10.70, suggesting that these three ports had moderate use efficiency in monitoring time, and their hinterland had a moderate level of outward-oriented economy.

The variation in PUI was consistent with changes in port cargo in most ports, which indicated that PUI had a good response to port throughput (Fig. 5). The throughput of Jingtang Port increased from 2.01×10^8 t in 2013 to 2.90×10^8 t in 2017, with PUI increasing from 14.23 to 20.60 over the same period. The PUI trend line indicated the highest value in 2015, which was consistent with the maximum throughput in 2013–2017. The PUI also increased with increasing throughput in Bayuquan Port from 2013 to 2016, and a similar trend occurred in Longkou Port from 2014 to 2017. The correlation between PUI and throughput was inconspicuous in Jinzhou and Yantai Port for their five points focused only in two years.

Table 3 Statistics of six ports' port-use prosperity index (PUI) around the Bohai Sea

Port	Region	Maximum	Minimum	Average
Bayuquan Port	Liaoning	14.27	8.00	10.70
Jinzhou Port	Liaoning	11.57	5.85	9.22
Yantai Port	Shandong	10.95	5.95	8.31
Longkou Port	Shandong	13.84	5.97	9.94
Jingtang Port	Hebei	20.60	14.23	17.75
Tianjin Port	Tianjin	16.42	10.39	14.14

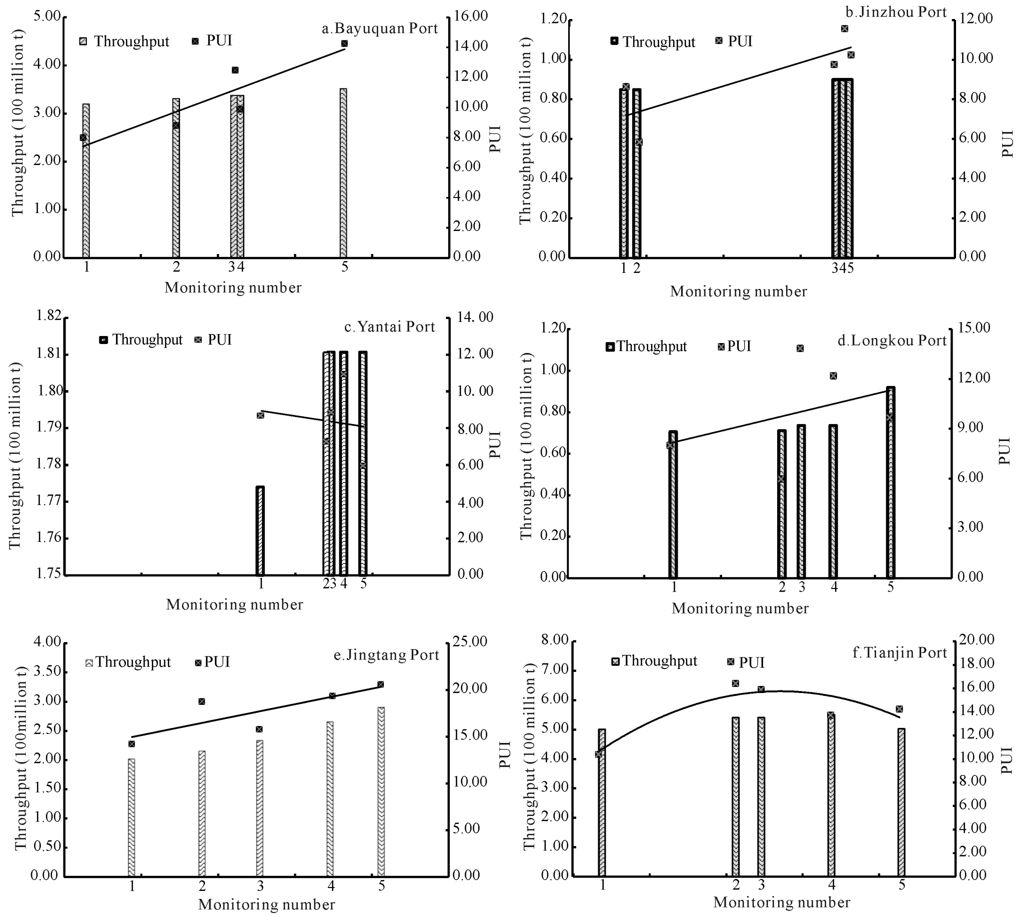

Fig. 5 Port-use prosperity index (PUI) changed companying with port throughput in six ports around the Bohai Sea. 1, 2, 3, 4, 5 in x-axis of each picture represent monitoring number and its image acquisition time show in Table 1

To verify the representativeness of cases in the randomly selected times to the whole situation, we used data from 2016 as an example and compared the results with those based on data from the five monitoring periods. The monitoring times for Yantai, Jinzhou, Longkou, Bayuquan, Jingtang, and Tianjin Ports were 4, 3, 2, 1, 1, and 1, respectively. The average PUI was highest in Jingtang Port (19.36), followed by those of Bayuquan and Tianjin Ports (14.27 and 13.73, respectively). Yantai Port had the lowest PUI value. Fig. 6 demonstrates that although the monitoring frequencies were different for each port, the PUI values in 2016 were similar to those calculated using the data from the five monitoring periods.

3.3 Verify of PUI by port cargo throughput

In most ports, the performance of port operation is represented by port cargo throughput, which quantitatively describes the amount of cargo shipped through a port within a certain period (Notteboom et al., 2001). With the development of containerized cargo transportation, container throughput came into use as a quantitative indicator to describe the number of containers shipped through a port (Park and Prabir, 2004). To verify authority

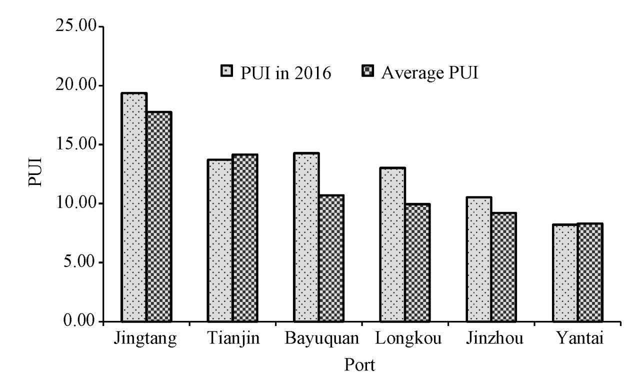

Fig. 6 Comparison of port-use prosperity index (PUI) in 2016 and average PUI of five monitoring times around the Bohai Sea

of PUI in port efficiency of six ports around the Bohai Sea, the annual port cargo throughput data for each port during 2013–2017 were collected and normalized by the total length of coastline. The PUI data also needed to be averaged if monitoring occurred more than once in one year. Then, one PUI point or the averaged PUI values point for a port in one year will be compared to the corresponding port cargo throughput data. Finally, 21 pairs of data were available to verify reliability of PUI in indicating of port operational performance. The PUI value and cargo throughput value were positively correlated with the linear correlation coefficient $R^2 = 0.5963$ (Fig. 7). A linear simulation equation $y = 0.7652x + 3.7877$ is established. This means that PUI could be an appropriate alternative for cargo throughput to indicate the performance of port operation. Cargo throughput can also be retrieved via the linear regression simulation equation based on PUI, which can be monitored and calculated by remote sensing images of the ports.

4 Discussion

Although port throughput can effectively indicate the utilization degree of a port, it is usually difficult to obtain port throughput data, and the authenticity of the data is hard to guarantee. The automatic identification system of ships serves as an important data source to manage a ship's basic performance, operating position, direction, and status, and it is therefore useful in port-use analyses (Adland et al., 2017; Zhang et al., 2019). However, ship automatic identification system data are not only large in volume but also difficult to interpret, making the compilation and retrieval of useful information time-consuming (Prochazka et al., 2019). In contrast, the use of satellite remote sensing images to monitor and evaluate docked ships in ports as well as the PUI proposed in this study provide not only a means to rapidly monitor the number and scale of port ships but also a method to assess port-use efficiency in real-time and in a more direct and practical way.

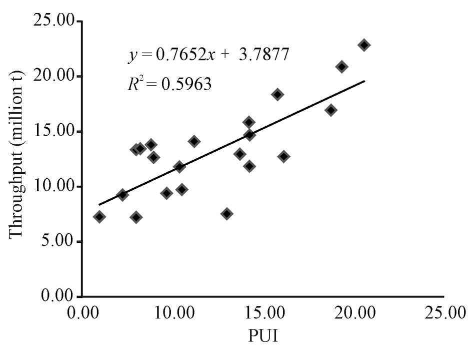

Fig. 7 Relationship between port-use prosperity index (PUI) and port throughput in six ports around the Baihai Sea during 2013–2017

The PUI can readily be obtained by monitoring docked ships based on high spatial resolution imagery, which can objectively and rapidly reveal the port utilization degree in monitoring times and avoid interference of port management in the port cargo throughput data. Long-term monitoring of the PUI of different ports in a region can not only reflect the differences in use efficiency between ports but also provide a basis for improving port management efficiency. Regional differences of outward-oriented economic development in the hinterland around each port can also be elucidated. The linear relationship between PUI and port throughput enables the latter to be calculated using remote sensing technology. However, the retrieval model was only preliminary because of the limited test samples, as we all know ports use efficiency does vary with changes of year and season. Therefore, the retrieval model should be comprehensively optimized in our future work upon the obtainment of a database covering different regions, years and seasons.

Regional differences existed between the studied ports around the Bohai Sea. The PUI values of Jingtang Port is the highest, which was reflected by the large number of ships, high proportion of large ships, and large ship plane area. This means the Jingtang Port was busiest and higher prosperity in terms of port efficiency, Tianjin and Bayuquan Ports jointly ranked second in terms of port prosperity and had a relatively high port-use efficiency, whereas Longkou, Jinzhou, and Yantai Ports had lower port-use efficiency, with PUI values below 10. The differences of the port PUI value in this paper is similar to port throughput report by Jiang (2018). However, the single PUI value is an instantaneous reflection of cargo ship docked in the port, it fluctuated with seasons or month or week. The average value of PUI monitored in several different times eliminates the impact of extreme data. It can reveal the total business of port operation. According the average PUI of six ports around the Bohai Sea during 2013–2017, the construction scale of Jingtang Port can be expanded to meet the rapid regional economic development in the area. The marketing strategies of Longkou, Jinzhou, and

Yantai Ports should be improved to widen the market for cargo transportation and improve port efficiency while avoiding further expansion of port construction over the short term.

5 Conclusions

To describe the degree to which the ports are used, this study employed high spatial resolution satellite images to establish the PUI. Docked ships in six ports around the Bohai Sea were monitored and quantitatively analyzed. The results showed that high-resolution satellite images can easily monitor the number, scale, and plane of ships docked in a port, and the PUI can be calculated using a ship's total plane area and length of docked coastline. The PUI is therefore an objective and practical index to evaluate port-use efficiency for all ports. It was significantly related to port throughput and can be used to simulate port throughput. The average PUI of Jingtang, Tianjin, and Bayuquan Ports around the Bohai Sea exceeded10.0, suggesting that these three ports were the most busily used and had higher use efficiencies, whereas Longkou, Jinzhou, and Yantai Ports had average PUI values of less than 10.0, suggesting that their operation and management should be improved. The PUI proposed in this paper is an important index to evaluate efficiency of port use instead of port throughput. It can be obtained by remote sensing images easily and used for improvement of port operational efficiency, port planning and scale control, and regional export-oriented economic development status monitoring.

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