TOWARDS DETECTING FRESH SUBMARINE GROUNDWATER DISCHARGE AT THE LAIZHOU BAY (SOUTHERN BOHAI SEA, CHINA) BY REMOTE SENSING METHODS

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ABSTRACT

Low-salinity groundwater reserves beneath the sea bottom and submarine groundwater discharges (SGD) are of great importance in the use and management of coastal water resource. A preliminary hydro- morpho-geologic analysis allows for considering the presence of low-salinity groundwater in the offshore of the Laizhou Bay (Southern Bohai Sea, China). In order to detect the potential SGD the analysis of the Sea Surface Temperature (SST) anomalies has been carried out by Landsat images in the seasons when seawater and groundwater are characterised by the largest difference in temperature. The main outcomes of the study are the following. At the nearshore scale, along the intertidal zone of the Southern bay, where the unconfined aquifer discharges, patchy cold water anomalies occur, approximately in the same positions in different tide conditions. At the embayment scale in the Eastern Laizhou Bay where the confined aquifer is likely exposed, cold water anomalies are spread out.

1. INTRODUCTION

Groundwater plays an important role in the environment: it replenishes rivers and wetlands and supports wildlife habitat; it is used as drinking water and also in agricultural and industrial activities. Around the world, groundwater resources are under increasing pressure caused by the intensification of human activities and other factors such as climate changes.

The presence of offshore low-salinity groundwater reserves below continental shelves is a global phenomenon (Post et al., 2013). They occur at nearshore, embayment and shelf scales (Bratton, 2010) depending on their genesis and hydro- morpho-geologic setting of the inland and the sea sectors. Low-salinity palaeo-water beneath the continental shelf is generally groundwater of confined aquifers trapped during sea level lowstands while modern water seeps from the intertidal zone are groundwater of unconfined-semiconfined aquifer systems extending seaward.

It is important to investigate the potential occurrence of offshore low-salinity groundwater for a series of reasons. For instance, the knowledge of the continental groundwater flow in the coastal aquifer extending beneath the sea bottom allows to improve the understanding of the hydrological cycle. Moreover, it is necessary to identify new strategic low-salinity water reserves because the expected scenarios of water scarcity. In addition, it is unclear how and how much submarine low-salinity water discharge impact on other processes such as biological, geochemical, oceanographic and the if human interventions impact on the groundwater discharge.

The detection of offshore low-salinity groundwater reserves can be detected by various methods. Directly by drilling programs, offshore wells allow the water sampling and the direct aquifer characterization. Indirectly by geophysical investigations, towed Continuous Electrical Tomography and Airborne Electromagnetic are suitable for this purpose, but generally they provide data in relatively shallow water depth (e.g., Tosi et al., 2011; Teatini et al., 2011). Such methods are very expensive and are appropriate at local scale. To reduce the extensive efforts and to parallel gain information on groundwater over large spatial scales, many authors used thermal-infrared (TIR) sensors mounted on aircrafts and satellites (Mallast et al., 2013; Danielescu et al. 2009; Johnson et al. 2008; Shaban et al. 2005). Advanced thermal infrared sensors have the potential to monitor costal water surface temperature (Xing et al., 2006a, 2006b, and 2014). Groundwater is less dense than seawater and forms buoyant cool water ‘‘plumes’’ and more diffuse discharges. This method detects temperature contrasts between the inflowing groundwater and the water body (river, lake, and ocean). The resulting thermal anomalies reveal potential groundwater discharge locations over large spatial scales.

In the coastland of the Laizhou Bay (Southern Bohai Sea, China), the groundwater flow and distribution are controlled by various geological factors such as subsoil architecture, fault presence, geomorphology, paleogeography, climate, and hydrology. Groundwater properties are characterized by complex variations in

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both the horizontal and vertical direction (Wen et al., 2012). Many researches were focused on the saltwater intrusion in the Laizhou Bay coastland (e.g., Xue et al., 2000; Han et al., 2010, Braga et al. 2013b), but poor information is still available about the input of fresh water into the sea by submarine water discharge (SGD).
The Laizhou Bay (Fig. 1), and in general in the Bohai Sea, are characterized by shallow water depth.
The bathymetric map (available from http://fvcom.smast.umassd.edu) shows water depths less than 70 m hence when the sea level was about 120 m below the present one (i.e. Last Glacial Maximun) most of the Bohai Sea was an alluvial plain. Consequently, Pleistocene freshwater are probably trapped into aquifers beneath the continental shelf.

Fig 1. Overview of the Laizhou Bay and the two study areas

This work is part of the Dragon 3 Programme, Project EPHESUS "Ecological and Physical Effects of the Surficial and groundwater exchanges between land and Sea" (ID.10558), which aims are: i) to develop an integrated monitoring approach by satellite products, in situ measurements and hydrological models; b) to provide detailed information for an understanding of hydro- morpho- geological processes on coastal areas (Braga et al. 2013a).
The goal of this work is to evaluate the capability of the remote sensing methods to detect the evidence of SGD as signal of the presence of offshore low-salinity groundwater reserves. Our basic idea is to search SGD where the groundwater can leaks from the seabed because of particular hydraulic, morphologic, and geologic conditions (Bratton 2010).

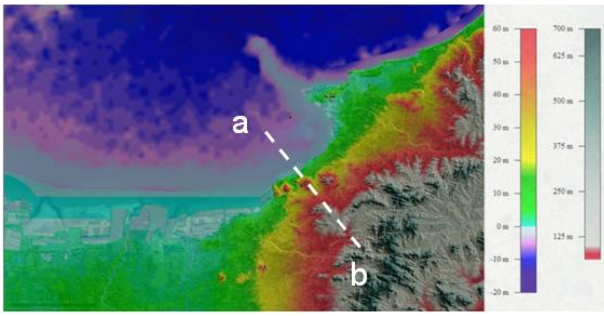
2. DATA AND METHODS

The hydrogeologic, geomorphologic and geologic settings were investigated by means of accessible data obtained from the literature and open access dataset. SRTM (Jarvis et al., 2008) and bathymetric data have been used for developing the morphologic model while subsoil characteristics (Congxian and Ping, 1991; Liu et al., 2009; Cheng, et al, 2004, Cheng et al. 2014) and water table measurements and groundwater characteristics (e.g. Ma et al., 2007, Han et al., 2011, Han et al., 2012; Wen et al 2012) for gaining the hydro-stratigraphic sketch. Information on the occurrence of tectonic lines has been available from Wang et al., 2006 and Liu et al., 2008.
Several Landsat ETM + band 6.2 (high gain) data and Landsat 8 OLI band 10 (10.9 µm) data covering respectively the years 2000 to 2003 and 2013 to 2014, with a cloud cover of less than 15 %, were analyzed.
All data were provided with a spatial resolution of 30 m, resampled using cubic convolution (USGS 2011).
First processing step included the radiometric correction, converting the digital numbers (DN) to Top Of Atmosphere (TOA) Radiance, following the method presented by Chander et al. (2009). The next step was to convert TOA radiance to surface radiance values with an atmospheric correction using appropriate local values for several parameters (Coll et al., 2010). Atmospheric transmissivity, upwelling and downwelling radiances needed for the atmospheric correction of the thermal data were obtained through NASA (http://atmcorr.gsfc.nasa.gov), the web-based Atmospheric Correction Tool that is based on MODTRAN (Barsi et al. 2003, 2005). The final step converted radiance values into brightness temperature in Kelvin and then in Celsius degree, applying the inverse of the Planck function. Lastly, to exclude land pixels, the normalised difference water index (NDWI) was calculated from each image. On the resulting NDWI image, a threshold was applied for distinguish values representing water features (McFeeters, 1996).
The resulting atmospherically corrected SST data represent the skin temperature of the water and, therefore, less than 1 mm of the uppermost water layer. This layer tends to be about 0.1 K colder than lower water masses due to evaporative heat loss, sensible heat flux and longwave radiation (Wloczyk et al. 2006; Donlon et al. 2002).
The quasi-simultaneous MODIS optical data were also used for analysis the results derived from Landsat TIR data.

3. PRELIMINARY SKETCH OF THE HYDRO-MORPHO- GEOLOGIC SETTING

The investigation carried out using available data points out that the hydro- geo- morphologic setting of the Laizhou Bay let us suppose the occurrence of low-salinity aquifers beneath the sea.
Groundwater can discharge from the seabed at the nearshore and embayment scale because of the piezometric gradient and the subsoil architecture of the Quaternary Units. Low-salinity groundwaters can seeps along subsoil discontinuities such as incised valley, paleochannels, and tectonics faults. Regarding this latter, to note the presence of the active Tan-Lu fault

zone in the Laizhou Bay (Wang et al., 2006 and Liu et al., 2008).



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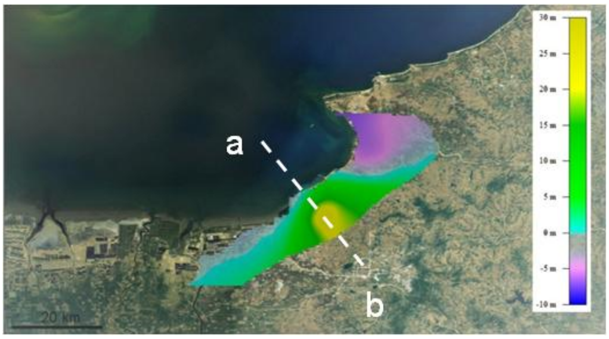

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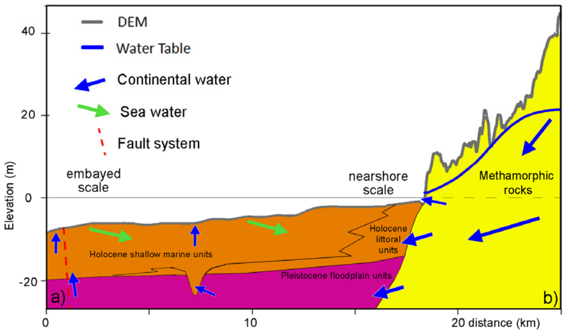

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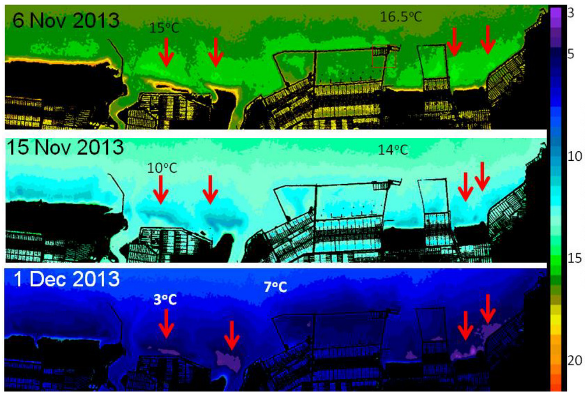
Figure 2. Hydro- geomorphological setting of the Southern and Eastern Laizhou Bay: A) SRTM and bathymetric data; B) water table level; C) hydro-stratigraphic sketch.

4. PRELIMINARY RESULTS FROM RS

This study focus the investigations on the presence of thermal anomalies in two study areas, the Southern and Eastern Laizhou Bay, where groundwater discharges can most likely be expected, as suggested by their hydro-geological setting.

In the Southern Laizhou Bay, TIR images allowed to map several thermal anomalies related to outflows of fresh water plumes with temperatures lower than the minimum seawater temperature recorded in the area. The Fig. 3 shows that some patchy cold water anomalies occur in different days (and in different tide conditions), along a shore strip of about 5 km. They are evident also if the absolute mean temperatures decrease and are characterized by a direct connection to the coast. These aspects maybe commend to a shallow or terrestrial emergence.



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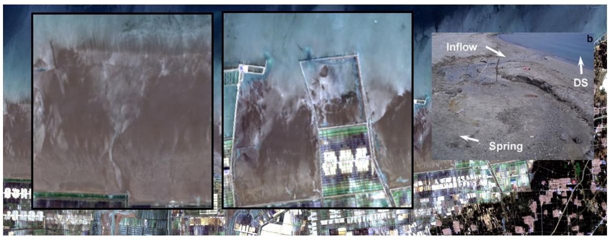

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Figure 3. Cold anomalies are identified along a shore strip of about 5 km in the Southern Laizhou Bay. Red arrows indicate the location of cold anomalies.

Moreover, the cold anomalies are approximately in the same locations over 20 days: it potentially indicates a continuous groundwater discharge. In the intertidal shore, the presence of some geomorphological features could be related to the observed anomalies and then potentially to groundwater inflow, (i.e. erosion channels of an upstream located terrestrial spring). This is more evident during low tide.

Fig. 4 shows the SST anomalies near the Southern Laizhou Bay coast.

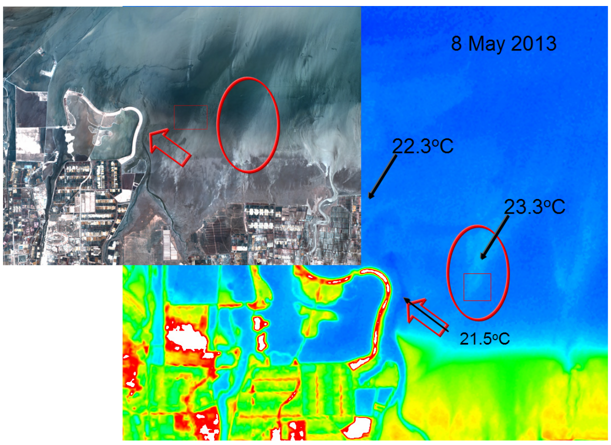

Figure 4. SST anomalies in the Southern Laizhou Bay.

The increase and decrease in SST may indicate the two different types of surface input, and the warm water discharges might be due to the SGD which experienced a longer flowing distance and received more sun heat when the tidal level was low.

Extending from the nearshore to the embayment scale, cold water anomalies are spread out in the Eastern Laizhou Bay where there may be considerable SGD input (Fig. 5). Cold water could derive from diffuse groundwater discharges as shown by hydrogeological investigation. The high SST in summer makes the temperature difference more evident for tracing the pattern of groundwater seepage. They do not have a direct connection to the coast, which suggests a deeper submarine emergence.

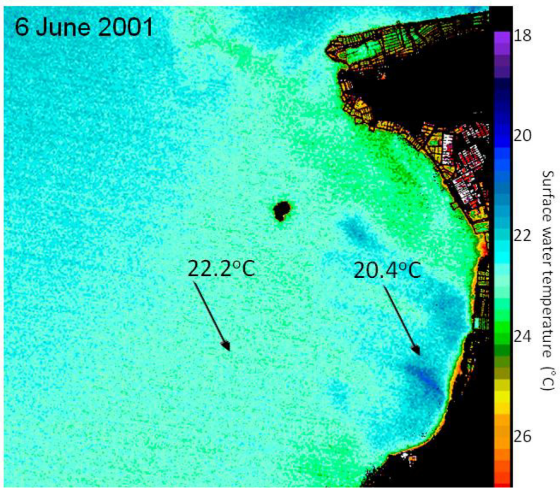

Figure 5. Cold water patches observed at the eastern Laizhou Bay in summer.

Fig. 6 shows an interesting cold dot in SST in summer in the eastern Laizhou Bay, which was not due to atmospheric effects and image processing. This anomalous feature is detected a few km off-shore at water depth of 6-8 m. It represents an exception since it has no direct connection to the coast and is probably of submarine origin. Groundwater likely seeps from the sea floor where the confined aquifer is exposed. It shows slightly smaller ΔT values that is the effect of the vertical mixing and heat exchange between the seawater and the discharging and ascending groundwater.

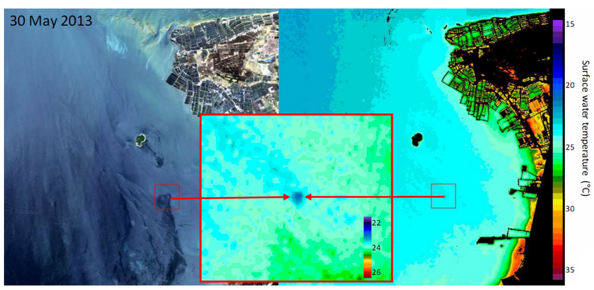

Figure 6. Anomaly in SST at the eastern Laizhou Bay show possible SGD as a cold spring in summer.

Over the last 10 years, as shown in Fig. 7, the extensive anthropogenic pressures on the nearshore area have significantly changed the hydrogeomorphologic setting in the Eastern Laizhou Bay. Groundwater resources and discharges may be impacted by the intensification of human activities.

Figure 7. Land-cover change in the Southern Laizhou bay: on the right year 2000, on the left year 2013.

Fig. 8 shows the presence of floating ice in the Eastern Laizhou Bay. Severe weather condition occurred with snow in the land and ice in the sea. The ice is formed by both seawater and freshwater of Yellow River, which drifts into Laizhou Bay (Zhang et al. 2013). The groundwater discharge could contribute to the ice formation in this part of the bay.

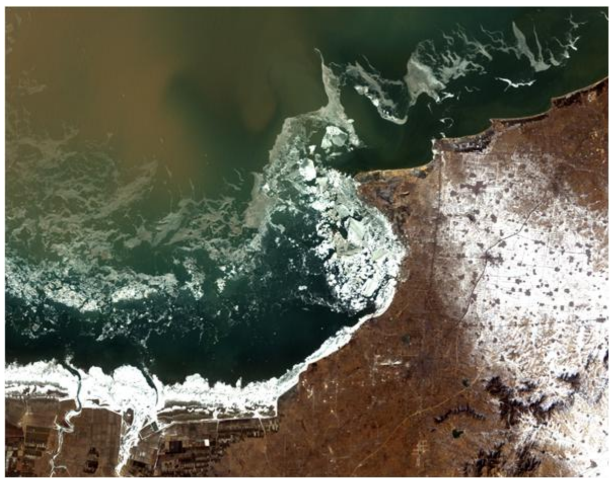

Figure 8. Landsat image acquired on 12 January 2003. The presence of floating ice is evident.

The SST map, obtained by the thermal band of the Landsat image acquired on 12 January 2003 (fig. 9), shows the warmer water plumes in the Eastern Laizhou Bay. During winter, SGD could be relatively warmer than the very cold surroundings. These patterns are consistent with the cold SST detected during summer.

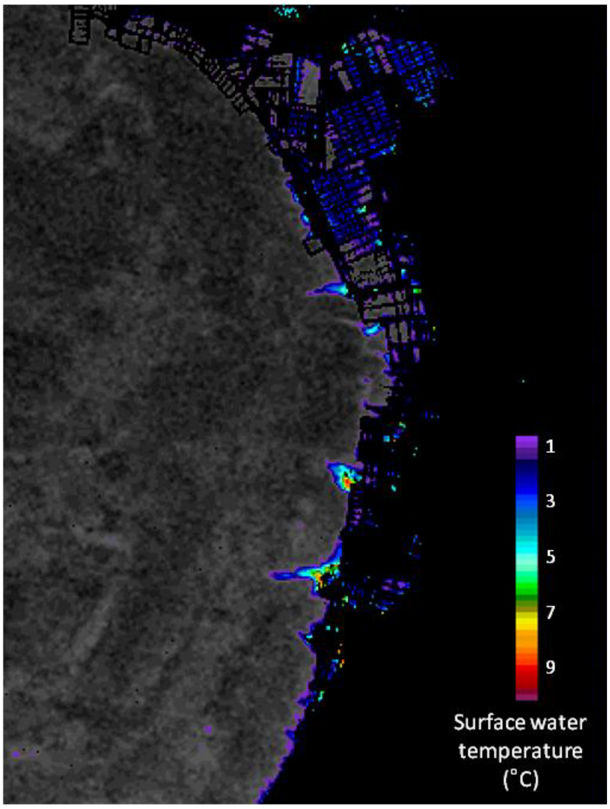

Figure 9. SST map of the Landsat image acquired on 12 January 2003. Relative warmer waters near the coast might be due to SGD in winter in the Eastern Laizhou Bay

5. CONCLUSIVE REMARKS

Many researches were focused on the saltwater intrusion in the Laizhou Bay coastland, but poor information is still available about the input of fresh water into the sea by Submarine groundwater discharge (SGD). The analysis of available hydro- morpho-geologic data allows to speculate on the extending of the aquifer system and groundwater flow beneath the bay. They can contain paleo - and modern- low-salinity groundwater at the nearshore and embayment scales.
In order to drive effective in situ hydrogeologic surveys, a preliminary investigation has been performed by remote sensing methods through the analysis of thermal data acquired by the Landsat constellation. Suitable to this investigation is the analysis of Sea Surface Temperature (SST) anomalies. Satellite images have been selected for different seasons, i.e. when seawater and groundwater are characterised by the largest difference in temperature, with the aim of detecting different types of water.
SST anomalies were observed both in the Southern and Eastern Laizhou Bay during summer and winter seasons. The interpretation of these anomalies, even taking into account the hydrogeologic setting of the areas where they occur, shows that SST anomalies are not related with long-shore circulation or river discharge and that there may be associated to SGD.
The analysis of TIR images can conveniently address hydrogeological field investigations permitting to map features, both localized and diffuse, such as gradients and anomalies associated to submarine groundwater seeps.
In addition, in the first step of the study, the satellite multi-temporal data sets allow to identify variations of the pattern and spatial extent of the groundwater discharges in relation to seasonal and interannual hydrological trend, otherwise difficult to detect by in situ measurements.
Certainly, other specific investigations in the areas of interest are required to calibrate the remote sensing outcomes and validate the SGD occurrences, for instance the Radon and Radium isotope assessment and geophysical surveys.
Finally, there are good reasons to investigate groundwater flow, transport and storage in the coastal area: possible future water scarcity due to overexploitation, pollution, and climatic changes can require the identification of at least temporary alternative fresh or low-salinity water supplies. For its intrinsic complexity Laizhou Bay is clearly a key site to test methodologies.

6. ACKNOWLEDGMENTS

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