An Integrated WebGIS System for Shallow Landslide Hazard Early Warning

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Abstract

The landslides are considered as one of the most dangerous natural disasters and can cause catastrophic influence on society. Therefore, improving the effectiveness of landslide early warning systems is an urgent requirement. The heavy and/or prolonged rainfall is the main factor that has triggered most of the landslide events. In this study, we propose the integration of a geotechnical model—LS-RAPID and a hydrological model—RRI in a WebGIS system to enhance the accuracy and efficiency of shallow landslide hazard early warning for a small basin in Ha Long City, Vietnam. LS-RAPID model is applied to determine potential landslide hazard areas and RRI model is employed to identify subsurface water levels. The system utilized real-time rainfall data from an automatic weather station and forecasted rainfall data from the GFS server as input data for the RRI model running inside the WebGIS server. By combining simulated results from LS-RAPID and RRI models, the integrated WebGIS system allows predicting the occurrence of landslide hazard in both location and time. With the ability to deliver highly accurate results in a short time, the system can be very helpful for the authorities at all levels in making early landslide hazard warnings that mitigate disasters in mountainous areas.

Keywords

WebGIS • Landslide hazard • Subsurface water • LS-RAPID model • RRI model • IDV

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Introduction

Due to the widespread ability and destructive power, landslides have claimed many lives and severely hindered the economic development and urbanization of many countries. To mitigate the landslide disaster, especially human casualties, the most effective method is to identify and early warn the location and time of landslide hazards. Brabb (1991) concluded that if the landslides could be predicted early, more than 90% of the losses could be avoided.

Locating landslide initiation is very important for disaster preparedness and response. However, in order to effectively deal with landslide disasters, processes of both the initiation and the post-failure movement should be predicted (Sassa et al. 2010).

It is well known that subsurface water generated from heavy and/or prolonged rainfalls increases the pore water pressure at potential sliding surfaces and reduces the soil

N. Casagli et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*,
ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60311-3_22

strength (Reichenbach et al. 1998; Ekanayake et al. 1999; Collins and Znidarcic 2004). Therefore, to be able to accurately simulate and predict the location and time of landslide hazards, the subsurface water level needs to be taken into account (Bogaard and Greco 2014; An et al. 2016).

WebGIS is a combined product of geographic information system (GIS) and internet technologies (Miao and Yuan 2013), and is used to analyze and display the spatial data. With the rapid development of internet and Web technology, sharing geographic information and broadcasting spatial decision in emergencies through the WebGIS system are considered as one of the fastest and most effective methods (Zhang et al. 2011; Li et al. 2015; Chen et al. 2016; Mamai et al. 2017). Hence, WebGIS can play a significant role in preventing and mitigating landslide disasters (Yu et al. 2007; Pessina and Meroni 2009; Li et al. 2010; Miao and Yuan 2013).

In addition to the popular WebGIS systems built to inventory occurred landslides (Devoli et al. 2007; Yanxi et al. 2009; Dahlhaus et al. 2011; Huang et al. 2013; Chen et al. 2016), some WebGIS systems have been established for monitoring and early warning of potential areas of landslides. In most of these early warning systems, landslides are often predicted by empirical methods based on susceptibility maps, empirical rainfall thresholds, and rainfall data (Huggel et al. 2008; Zhang et al. 2011; Hou et al. 2013; Rosi et al. 2017; Artha and Julian 2018). With this empirical method, WebGIS system can only predict about the period but cannot accurately indicate the areas where the landslides will happen. Some warning systems have integrated a landslide model within the WebGIS system for monitoring and warning the failure of single slopes (Li et al. 2010; Thiebes et al. 2013). In all aforementioned systems, the coupling of landslide hazard and hydrological models has not been exploited to improve the effectiveness of disaster mitigation at a basin (or larger) scale.

The capacity of the geotechnical model LS-RAPID (Sassa et al. 2010) and hydrological model RRI (Sayama et al. 2012) for predicting the spatial and temporal occurrence of landslide hazard was proved when verified with the reality (Ha et al. 2020). To improve the effectiveness of mitigating shallow landslide disasters, in this study, we propose a prototype of an integrated WebGIS system combining the LS-RAPID and RRI models into the WebGIS system. The following issues will be resolved:

- How should LS-RAPID and RRI models need to be integrated into the WebGIS system to support the authorities in early warning of shallow landslides?
- How do rainfall forecast and real-time rainfall data need to be acquired and processed to be automatically simulated by RRI model inside the WebGIS system?

Study Area

Located in the tropical monsoon region, Vietnam is one of the countries affected by the global climate change with abnormal weather events and frequent extreme rainfalls. The landslides are a common geohazard in the mountainous areas of Northern Vietnam. Therefore, the development of methods to help minimize losses related to landslide disasters is very important and urgent.

Ha Long City, Quang Ninh Province, Vietnam has a complex and diverse topography including hills, mountains, valleys, coastal areas, and islands. The hilly and mountainous terrain accounts for 70% of the city area and is concentrated mainly in the North and Northeast. The mountain ranges have an average height of 150 m to 250 m, tend to decrease towards the sea and are intertwined by the narrow valleys. Many households are living in high-risk areas affected by the landslides. According to statistics of the Department of Construction of Quang Ninh Province in 2016, 1,278 households living in 174 zones of high landslide susceptibility need to be relocated.

The pilot study area is a small basin (about 0.15 km^2) in Cao Thang Ward, Ha Long City. In this area, 3 shallow landslides were triggered by a historic rainfall in July 2015, in which 1 landslide destroyed 3 houses and killed 8 people. This rainfall event was the heaviest downpour in the city in 40 years with the highest rainfall intensity of 86 mm/h and 257 mm in 5 h. The province's economic damages caused by this rainfall was determined more than 100 million USD (Fig. 1).

Combining LS-RAPID Geotechnical Model and RRI Hydrological Model

In the LS-RAPID model, the effect of pore water pressure on slope stability due to rising water is expressed through the pore water pressure ratio (r_u) based on pore water pressure and total normal stress acting at the potential sliding surface (Sassa et al. 2010).

To identify areas of potential landslide hazards, the LS-RAPID model was applied with a range of r_u values corresponding to different scenarios of the water level (from no subsurface water to when subsurface water reaches to the ground surface). The results of applying LS-RAPID

Fig. 1 Google Earth satellite image of Ha Long City with locations of the study basin and the weather station

simulations have identified several potential landslide hazard areas (see areas A1, A2, B1, B2, C, D in Fig. 2). In each forecasted hazard area, three regions: landslide scarp, accumulation zone, and landslide initiation part (locating inside the landslide scarp) were distinguished. In each initiation part of potential landslide hazards, the threshold value of pore water pressure ratio (r_uT) activating the landslide is also estimated. The value of a r_uT is determined as the r_u value when a potential landslide starts to occur in simulations.

The coupling method of the hydrological—geotechnical framework is employing shallow landslide trigger: the subsurface water to connect the simulation results of LS-RAPID and RRI models.

Based on the observed rainfall and subsurface water level, the RRI model was calibrated and then applied to the rainfall data of the 2015 event. By applying the RRI model, subsurface water level maps for all simulation time steps are generated. From there, the various r_u maps for these time steps are created automatically.

To estimate the probability of landslide occurrence, the Risk Index (RI) is determined as $RI = r_u/r_uT$. In each forecasted hazard area, a landslide is likely to happen if the maximum RI is close to or higher 1 (as the maximum value of r_u in the initiation sources approaches or exceeds the r_uT).

For each time step, a RI map is produced by combining the r_u map of that time step and the r_uT map.

The framework coupling LS-RAPID and RRI models is described in more detail in Ha et al. (2020).

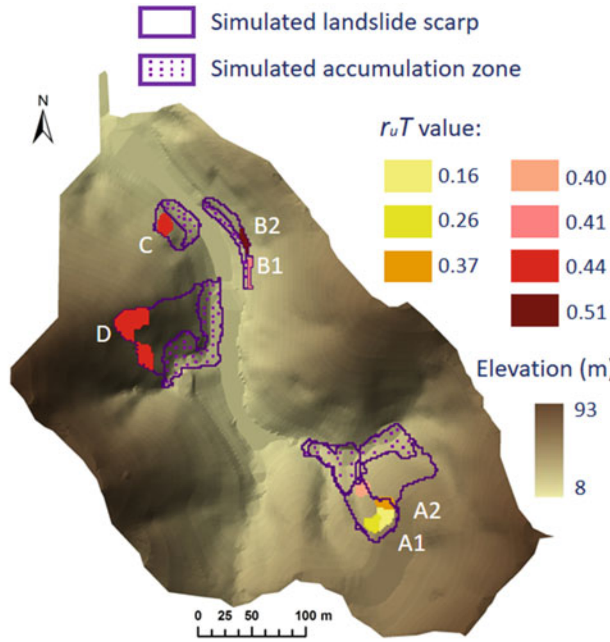

Fig. 2 Potential landslide hazard areas and predicted r_uT values at landslide initiation parts

Integrated System Architecture for Early Warning of Shallow Landslide Hazards

State-Funded Landslide Project (SFLP)

The State-Funded Landslide Project (SFLP) "Investigation, assessment and warning zonation for landslides in the mountainous regions of Vietnam" has been implementing for all mountainous provinces (37/64 provinces) of Vietnam since 2012. In the first phase of the project (ongoing), the WebGIS system has been used as a tool to fill the missing information of the occurred landslide and to update new landslide events. Its spatial database including maps of landslide inventory, controlling factors, and susceptibility zonation would support scientific research as well as contribute to local land use planning to improve the coping capacity of disaster prevention (Hung et al. 2017). In the second phase (not yet implemented), the SFLP has planned to transmit emergency information about the possibility of landslides in critical areas to the government and local authorities through the WebGIS system. Accordingly, through this research, LS-RAPID and RRI models were integrated into the SFLP WebGIS system as a pilot system to support decision-makers.

SFLP WebGIS System

Although the applications to build a WebGIS system are diverse, the general architecture usually consists of three tiers: database tier, application tier, and user interface tier. The SFLP WebGIS system was built with free and open-source software (Fig. 3).

The data tier is built with PostgreSQL database management system and its extension—PostGIS. PostgreSQL is a popular database management system, built with open

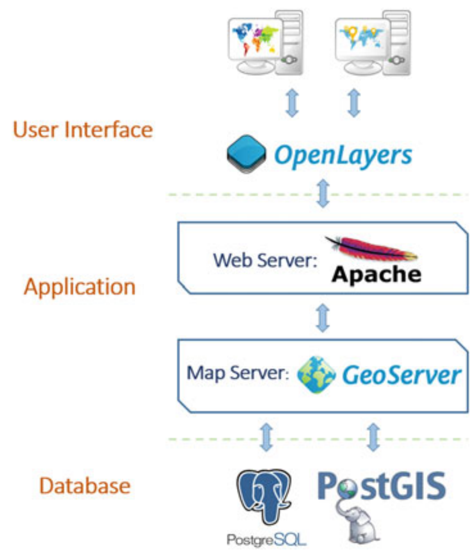

Fig. 3 The three-tier architecture applied for the SFLP WebGIS system

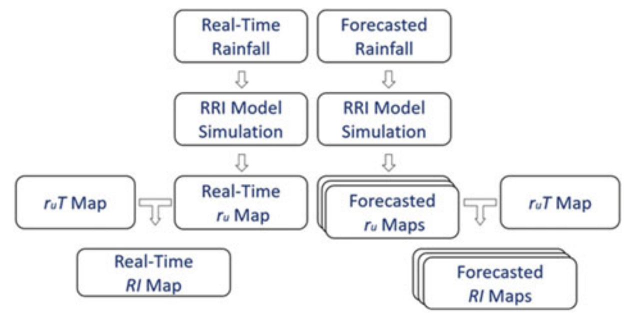

Fig. 4 Method for generating *RI* maps inside the SFLP WebGIS server

source and can be compatible with most popular operating systems. PostgreSQL is equipped with interfaces to connect to many programming languages like Python, PHP or Java. PostGIS is a spatial database extension of PostgreSQL. Through PostGIS, the location and map information of spatial objects can be easily queried.

At the application tier, to manage the work inside the server, the HTTP web server—Apache and the map server—GeoServer are chosen to use. Web server is a software used to receive and analyze requests from web users and return result information. GeoServer is used to perform services of managing geographic objects over the internet with the OGC (Open Geospatial Consortium) standards. GeoServer is also used to specify the visual styles (colors, shapes, transparency) of geographical objects stored in the PostGIS database.

At the interface tier, OpenLayers communicates with GeoServer via OGC standard. OpenLayers is a JavaScript library that helps to build interactive map tools on the web. With these tools, web users can easily manipulate maps and geographical objects on web browsers.

Integrate the Hydrological-Geotechnical Framework into the WebGIS System

The hydrological-geotechnical framework has been integrated with the SFLP WebGIS system in two separate phases. In the first phase, to identify areas at risk of landslide hazards and the thresholds of pore water pressure ratio (r_uT), the LS-RAPID model is applied to different scenarios of subsurface water level. While the simulation with the LS-RAPID model needs to be done before integrating with the WebGIS system, in the second phase, the RRI model needs to be applied automatically regularly within the SFLP server. In order to predict the time at which landslide hazards are at risk, variations in the subsurface water level need to be monitored regularly. From that, the maps of pore water pressure ratio (r_u) according to real-time and forecasted rainfall data can be generated. These r_u maps will be automatically combined with the r_uT map to generate *RI* maps and support warnings about the location and timing of possible landslide hazards in the near future. Figure 4 presents the main steps of the method of combining LS-RAPID and RRI models in the SFLP WebGIS server to identify *RI* maps.

The strategy of applying LS-RAPID and RRI modeling framework into 2 separate phases is very important for emergency situations in disaster management and warning because of the ability to optimize processing time. In addition, the RRI model has the ability to allow the simulation process to continue with newly updated data without having to restart from the beginning of the data series. This feature is very useful for the early warning system since rainfall data (real-time data and forecasted data) are regularly updated (Ha et al. 2020). Specifically for this study area, the time-consuming of acquiring rainfall data and generating a *RI* map for each time step by the author's personal computer range from nearly 1 min to a few minutes depending on the intensity of rainfall.

Connect Real-Time Rainfall Data

A weather station has been installed near the study area (about 1 km Northeast). The weather station consists of 3 main equipment (Vantage Pro2 equipment manufactured by David Instruments Corp): an outdoor station, a console, and a data logger. Rainfall data measured by a rainfall collector

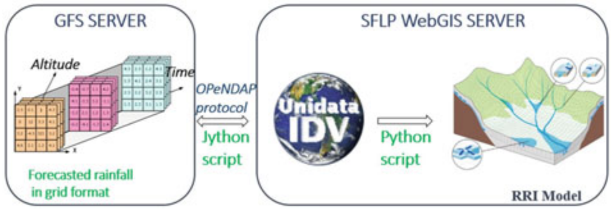

Fig. 5 Conceptual model of utilizing forecasted rainfall data from the GFS server

in the outdoor station are sent regularly to the console every 10 min by the solar-power transmitter. The data logger is employed to link the console and the "WeatherLink Cloud" of David Instruments Corp. With this method, newly updated data can be automatically displayed on the website "www.weatherlink.com" every 60 min.

Inside the SFLP server, every 60 min, the Python script is used to automatically connect to the website "www.weatherlink.com" and collect measured rainfall data. Whenever the rainfall data is updated, the Python script will update the input data file and send requests via the command line to the RRI model to perform simulations. The newly acquired rainfall data is also updated into the database in the PostgreSQL database management system so that it can display the rainfall data in time series to users when required.

Connect Forecasted Rainfall Data

To monitor and forecast of the risk of landslide hazards, real-time rainfall data is a requirement to simulate the hydrological process in the study basin. However, the preparedness is much more effective, and the damages caused by landslide hazards can be significantly reduced if forecasted rainfall data is also applied.

The Global Forecast System (GFS) is a meteorological forecast model produced by the National Centers for Environmental Prediction (NCEP)—USA. The GFS model provides forecasted rainfall data for the world four times a day

Fig. 6 The graphical user interface of the WebGIS on landslides "www.canhbaotruotlo.vn" which introduces the main achievements of the SFLP

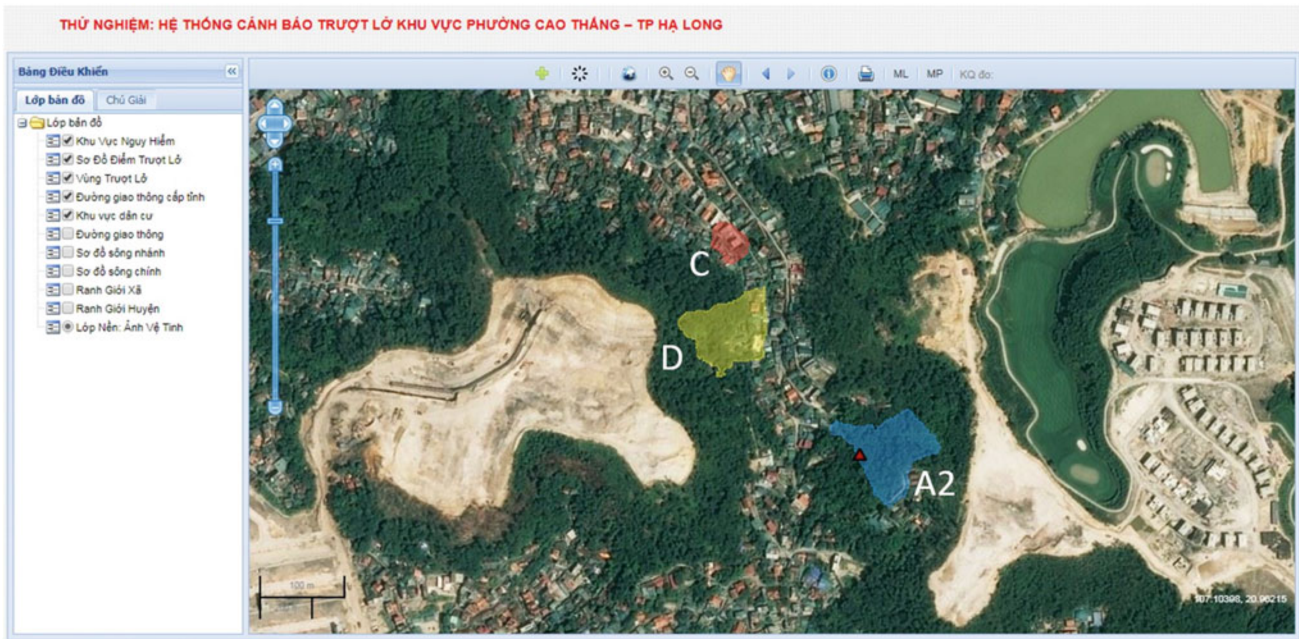

Fig. 7 Illustration of three warning levels for potential shallow landslide hazard areas would be shown in the WebGIS "www.canhbaotruotlo.vn"

(at 00, 06, 12, 18 Universal Time Coordinated). The forecasted rainfall data from the GFS model is in a grid format, with a spatial resolution of 28 km and a time resolution of 3 h.

A typical feature of grid data is that the coordinates are stored by longitude and latitude, and time is a dimension of the data structure. These features allow the spatial and temporal relationships of continuous phenomena in the real world to be easily expressed (Di et al. 2003).

The grid data from GFS server is automatically accessible via OPeNDAP protocol. OPeNDAP stands for "Open-source Project for a Network Data Access Protocol". This is a server-client protocol that allows access and sharing of grid data given by Unidata and is widely used in the Earth Science community. A major challenge in using grid data is the huge database set. For the management and warning of natural disasters, the information processing time to make a decision should be shortened as much as possible. Therefore, it is not appropriate to download the entire database and then extract the data of the area and the time required to study. To optimize processing time, the required data of grid data must be determined on the GFS server side. Then the download and processing of data will be much faster.

There are many OPeNDAP client software widely used for connecting OPeNDAP servers and retrieving grid data such as IDV, MATLAB, GrADS, Ferret, and Pydap. Based on selection criteria such as software that needs to support the writing of programming applications, support for building server-client applications, support for reading and analyzing grid data, the IDV software has been selected for use inside the SFLP WebGIS server to address obstacles in identifying and downloading automatically forecasted rainfall data for the study basin (Fig. 5).

The IDV (Integrated Data Viewer) software is developed by Unidata. This is a Java-based software built to support the analysis and display of geoscience data. IDV is able to work with many types of data such as grid data, surface observations, satellite images, and radar data. An important feature of IDV software is the ability to identify and query geo-referenced datasets placed on remote servers. Therefore, by constructing additional functions for IDV with the Jython programming language (an implementation of Python to run on Java platform), a subset of grid data in the spatial range and time of study can be predefined and automatically downloaded to the server of the SFLP WebGIS system.

Results

As part of the SFLP project, a national WebGIS system "www.canhbaotruotlo.vn" has been developed for landslide inventory and early warning with a simple interface for users with diverse backgrounds. This WebGIS system is also considered as one of the interactive interfaces for landslide research among scientists, managers and local people.

In the first phase of the SFLP Project, the main result is the spatial database system for landslides. The database includes maps of landslide inventory and susceptibility zonation at 1:50,000 scale and information of landslide controlling factors. This database has been uploaded to the

WebGIS system to share with local authorities and people about real conditions and potential risks. In addition, the shared information can contribute significantly to scientific research. Local people are encouraged to participate in the WebGIS system to fulfil missing information of the landslide inventory, update the new landslide areas and inform the signs of new landslides as detected. Therefore, WebGIS is also supported with tools that allow local people to easily inform the authorities and staff of the SFLP Project. This information, before verified, will be visualized differently from the style of official data.

In preparation for the second phase of the SFLP Project, the author proposes an early warning system for shallow landslides by integrating the coupled hydrological geotechnical framework in conjunction with the SFLP WebGIS system. This system (still under testing period) will be provided as a reliable reference to assist authorities in shallow landslide hazard early warning (Fig. 6).

The potential shallow landslide hazard areas A2, C, and D are being monitored with the application of the hydrological-geotechnical framework within the SFLP WebGIS system. Area A1 where a landslide occurred and areas B1 and B2 where reinforced by structural measures are not monitored. Figure 7 illustrates three warning levels that will be used to represent the risk status of the area being monitored. Three warning levels: safety (in blue), close monitoring (yellow) and danger (red) are determined based on the calculated Risk Index (*RI*) value range: $0 < RI < 0.2$ (safety); $0.2 \leq RI < 0.7$ (monitoring); $0.7 \leq RI$ (danger). The value of the *RI* index is used for each of the potential hazard area (A2, C, and D) to give a warning that the highest *RI* value is calculated in the landslide initiation parts of those areas.

Discussion and Conclusion

For preventing or mitigating landslide disasters, it is very important forecasting the process of landslide hazards in both location and time. In WebGIS systems utilizing empirical rainfall thresholds, the principal disadvantages are the occurrence (both location and time) of potential landslides are incapable to be determined correctly. In existing systems applying models for early warning landslides at a catchment or larger scales, the possible hazard areas are not identified. In addition, for emergency responses, the processing time for landslide simulating might be also an impediment. By taking advantage of the LS-RAPID and RRI models, the integrated system can support to forecast both the initiations and the runout processes of landslide hazards. Moreover, the application of two models at two separate phases brings a great advantage to the system in terms of the processing time necessary in emergency operations.

For the early warning system, in order to increase the accuracy between predictive and actual results, the uncertainty of the input data needs to be considered and improved. The resolution of the forecasted rainfall data from GFS is not high so that warnings are hard to be issued based solely on this data. However, these data can serve as a reference for the future trend of rain in the study area.

In this study, the geotechnical model LS-RAPID and hydrological model RRI are incorporated into the SFLP WebGIS system as a prototype for the shallow landslide early warning system. The real-time rainfall data from the weather station located near the study area and forecasted rainfall data from the GFS server are automatically extracted and used regularly as input data for the RRI model. From the simulation results, the subsurface water level can be estimated for each location. Therefore, potential area and occurrence time of landslide hazard can be forecasted and support decision-makers in issuing an early warning.

Acknowledgements This study is a part of the State-Funded Landslide Project (SFLP) "Investigation, assessment and warning zonation for landslides in the mountainous regions of Vietnam" and contributes to the Sendai Landslide Partnerships 2015-2025. The research was also financially supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and the Japan-ASEAN Science, Technology and Innovation Platform (JASTIP). The authors are immensely grateful colleagues from Vietnam Institute of Geosciences and Mineral Resources (VIGMR), MONRE for their support and valuable comments on this study.

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