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A WebGIS decision-support system for slope stability based on limit-equilibrium modelling

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ABSTRACT

Physically-based models are frequently applied for local landslide analyses and predictions in order to prevent the potentially disastrous consequences of slope failures. Limit-equilibrium modelling approaches are very common. However, the application of such models can be very time-consuming, and due to its two-dimensional nature, it generally has to be repeated for each profile that is investigated. In this study, the physically-based two-dimensional landslide model CHASM (Combined Hydrology and Stability Model) was implemented within a web-based GIS (Geographical Information System) environment for a study area in the Swabian Alb, Germany. The required input data for CHASM modelling were derived from a variety of data sources including geological maps, drillings, geophysical investigations, hydrological monitoring, laboratory analyses and literature sources. The implemented CHASM decision-support system is based on open-source software and utilises the WPS (web processing service) standard to execute the model algorithms on a server. The presented system allows the user to select from a variety of input data and model parameters to quickly perform limit-equilibrium analyses of slope stability. Simulation results are automatically stored to a database and can be visualised for interpretation. The implemented CHASM decision-support system represents an innovative prototype which demonstrates a promising approach to engage landslide modelling.

1. Introduction

Landslides are a hazard in many parts of the world and cause fatalities and significant damage every year. Turner (1996) states that the economic damage in the USA yields US-$ 1–2 billion in addition to 25–50 fatalities. For China, Yin (2009) estimates a direct annual economic loss due to landslides of approximately 10 billion RMB (approximately US-$ 1.3 billion) in addition to 900 fatalities. Even in Germany with its relatively low fraction of high mountain areas, the annual damage has been calculated to be as high as US-$ 150 million (Krauter, 1992). Consequently, quantitative predictions of landslides have been carried out by geotechnical experts and scientists for a long time (e.g. Coulomb, 1776; Terzaghi, 1925). Landslide modelling, along with experimental subsoil exploration and experience driven safety assessment, is one of the main tasks of slope stability practice (Janbu, 1996). Numerical models are applied to analyse the current stability status of slopes and to predict slope behaviour under certain conditions such as rainfall events or scenarios for environmental change. Moreover, models are used for the back-analyses of already failed slopes and for assessment of effectiveness of geotechnical stabilisation measures (Barla et al., 2004). Today, a variety of commercial software solutions are available for numerical slope stability assessment (e.g. GGU, XSlope, Slope/W, Slide, to name a few only). Despite the development of highly sophisticated numerical models such as finite-element methods (Spickermann et al., 2003; Petley et al., 2005; Keersmaekers et al., 2008) the relatively simple limit-equilibrium methodology is still widely applied (Abramson, 2002; Tinti and Manucci, 2008; Price and Freitas, 2009; Iovine et al., 2010). However, the application of local landslide models can be very time-consuming because detailed information on slope geometry, subsurface conditions and geotechnical characteristics have to be prepared for each slope profile analysed. Since the advent of GIS, scientists increasingly focussed on regional scale landslide analyses instead of single slopes. This research involved the preparation of landslide susceptibility, hazards and risks maps derived by various methodological approaches to aid spatial planning (e.g. Guzzetti et al., 2005; Bell, 2007; Chung, 2008; Rossi et al., 2010; Goetz et al., 2011). Some of the regional scale approaches integrate simplified limit-equilibrium methods, mostly in the form of the infinite-slope model (e.g. Dietrich et al., 1998; Hennrich and Crozier, 2004; Pack et al., 2005). However, until now there are not many published works on software tools in which standard limit-equilibrium methods are directly integrated into a GIS

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framework (Xie et al., 2004a, 2004b, 2006). When dealing with the computation of spatial data in general, and in particular with the integration of new functions into web-based GIS, it is of crucial importance to utilise international software standards to ensure the interoperability and transferability of the implementations. Such standards are developed by the Open Geospatial Consortium (OGC) (www.opengeospatial.org) which represents an association of GIS software developers, companies and universities. In the case of the WPS (web processing service), the OGC specifications define a standardised interface for offering processing capabilities within a geospatial data infrastructure. These do not limit the processing capabilities to familiar standard GIS operations such as polygon intersection, but also allow for complex process models such as combined hydrology-slope stability software e.g. CHASM (Anderson et al., 2008) to be offered. Whereas some of the OGC standards such as web mapping services (WMS) have already been successfully integrated within research projects, WPS have received less attention by practitioners and the scientific community. However, a recently published special issue of the journal Computers and Geosciences (Zhao et al., 2012) underlined the capabilities of WPS and more applications can be expected for the future.

This paper presents a new procedure for physically-based slope stability modelling within a web-based GIS environment, and illustrates the benefits of this flexible and time-saving approach and represents one of the first applications of the OGC standard web processing service in landslide research. The novel WebGIS application allows a complex model (in this case CHASM) to run using a web browser; the model is run on a server instead of a local computer. We explicitly recognise the scarcity of WPS utilisation in landslide research (Cannata et al., 2010; Rossi et al., 2010) and develop and implement a combined hydrology-slope stability model (CHASM) decision-support system utilising open-source software, developed according to OGC standards. The implementation of CHASM as a WPS shows the potential of this service to integrate complex simulation algorithms into web-based geospatial applications. CHASM software has already been applied successfully under various environmental conditions, for example in New Zealand (Wilkinson et al., 2000), Malaysia (Collison and Anderson, 1996; Lateh et al., 2008), Hong Kong (Wilkinson et al., 2002a), the Caribbean (Anderson et al., 2008), Kuala Lumpur (Wilkinson et al., 2000, 2002b), and Greece (Matziaris et al., 2005; Ferentinou et al., 2006; Sakellariou et al., 2006). For a study area in the Swabian Alb a wide selection of data sources was used to create a general subsurface model including geotechnical parameterisation of the respective materials. Moreover, rainfall scenarios and an adapted shear surface search routine were elaborated to facilitate an easy and time-saving application of the physically-based model CHASM to various slope profiles. The presented research was embedded into the Integrative Landslide Early Warning Systems project (ILEWS) which sought to develop and implement an integrative landslide early warning system initiated by field sensors, and delivering user-optimised warnings and action advice to end-users.

2. Study area

The study area of this research is located in the Swabian Alb, a lower mountain range in southwest Germany (Figure 1). The lithology of the Swabian Alb primarily consists of Jurassic clay underlying marl and limestone strata, of which the latter form a steep escarpment (*Albtrauf*) stretching in a southwest–northeast direction for some 200 km. Elevations reach up to 1000 m in the western part, and range between 600 and 800 m in the central and eastern sections. Landslides are a common geomorphological feature in the region due to geological conditions (Terhorst, 1997) and triggering impact of rainfall events, snow melting and earthquakes (Meyenfeld, 2009). In total, approximately 30,000 landslide bodies of various sizes and ages can be assumed for the entire Swabian Alb region (Bell, 2007). Several authors emphasise the importance of landslides for the relocation of the cuesta escarpment and the evolution to the present landscape (Bleich, 1960; Terhorst, 1997; Bibus, 1999), but slope failures also represent a significant geo-hazard in the present (Kallinich, 1999; Bell, 2007; Neuhäuser and Terhorst, 2007; Papathoma-Köhle et al., 2007). The most recent large landslide event was the Mössingen rockslide that took place in 1983. During this event approximately 6 million cubic metres of material were initiated by exceptionally wet conditions (Fundinger, 1985; Bibus, 1986; Schädel and Stober, 1988).

The study site of the described research is an area of approximately 2 km^2 located in Lichtenstein-Unterhausen. The lithology primarily consists of Upper Jurassic limestone and marl, and Middle Jurassic clay. The slopes are in most places covered by slope debris from Pleistocene solifluction and landslide activity. Fluvial deposits and tufa of late glacial and Holocene age cover the valley bottom. At several locations volcanic tuff is displayed in the geological maps, originating from tertiary volcanic activity.

The slope is dominated by two adjacent large landslide bodies which are seasonally reactivated leading to ongoing damage to infrastructure (Figure 2). Another notable geomorphological feature is a scree slope formed of loose limestone. The limestone rocks originate from the outcrops of Upper Jurassic limestone stratum in the landslide head scarp areas and indicate a high rockfall activity.

The study area Lichtenstein-Unterhausen has been subject to landslide-related investigations since 2002. Initially, research focused on the assessment of current landslide activity and the reactivation process (Bell, 2007), the characterisation of the landslide body by geophysical methods (Bell et al., 2006), landslide hazards and risks (Bell, 2007), and vulnerability of given elements at risk (Papathoma-Köhle et al., 2007). Between 2007 and 2008, the existing slope movement monitoring system was significantly extended by the ILEWS project (Bell et al., 2010) by additional manual and one automated inclinometer (Figure 3). Moreover, an extensive hydrological monitoring system, comprising TDR sensors and tensiometers located in three depths between 2 and 10 m at nine different locations, was set up to assess soil suction and volumetric water content changes. In addition the used tensiometers were able to measure also excess pore water pressures (UMS, 2007). Additional geophysical measurements using seismic refraction and geoelectric resistivity monitoring were carried out to investigate subsurface characteristics and slope hydrology, respectively.

The ILEWS project assessed an extremely slow annual downslope movement of 2–3 mm which occurs at the interface of slope debris and the underlying bedrock in a depth of approximately 15.5 m, as well as within the slope debris itself in approximately 8.5 m depth. Slope hydrology was found to play an important role for the reactivation of slope movements which primarily occur after snow melting in spring and strong rainfall events in autumn. However, significant and reliable hydrological thresholds of landslide reactivations could not be determined due to the complexity of subsurface hydrology.

3. Methods and data

3.1. Combined hydrology and stability assessment

For slope stability analysis the physically-based landslide simulation model CHASM (v4.12.5) was used. This software includes a two-dimensional finite difference hillslope hydrology model to predict transient pore pressures, and integrates these into the Mohr–Coulomb equation to calculate effective stress. Within CHASM, the slope is divided into a series of columns of which each is subdivided into regular cells for which infiltration, detention storage, and unsaturated and saturated flow regimes are simulated. Rainfall infiltration into the top cells is controlled by the infiltration capacity. Unsaturated vertical

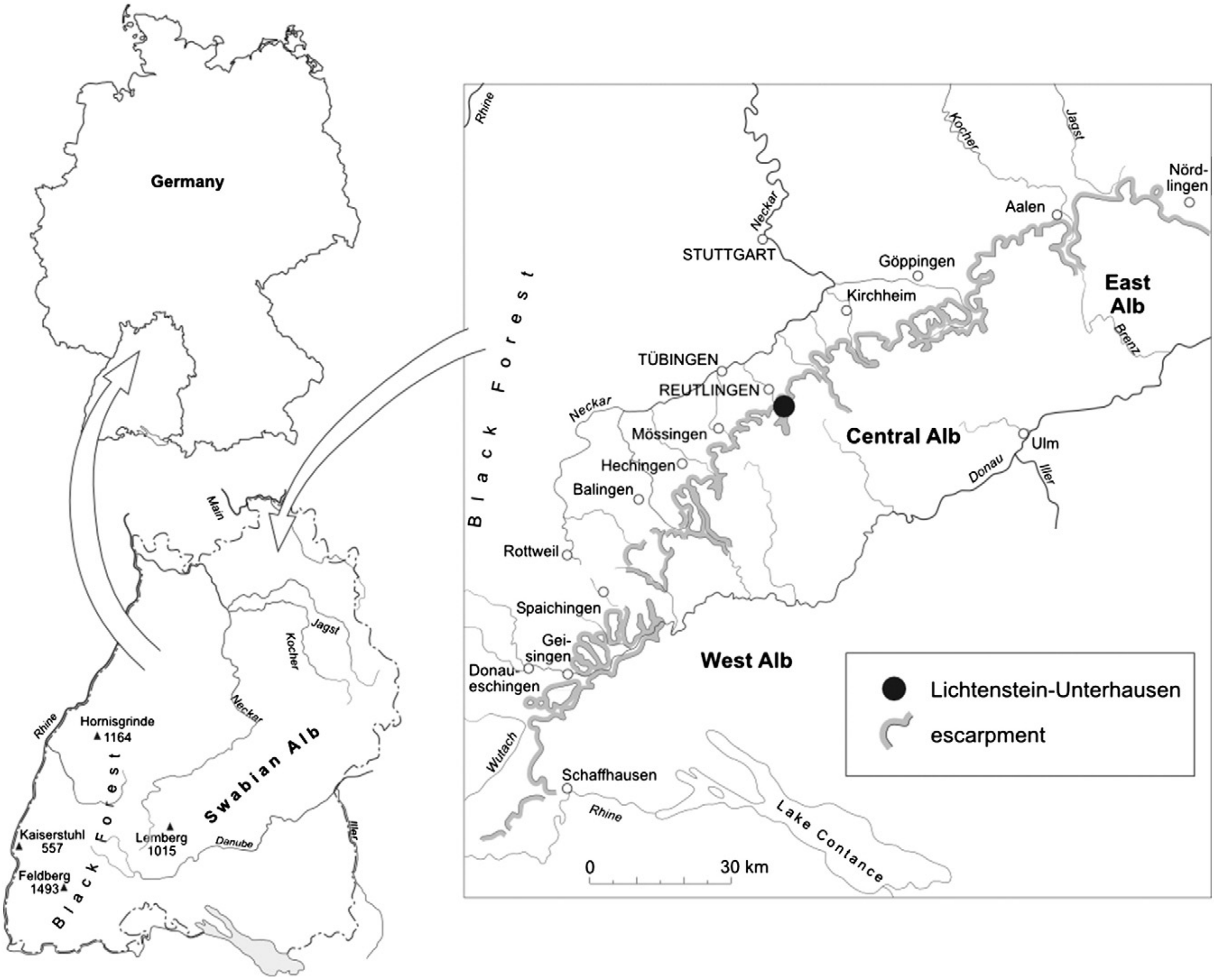

Fig. 1. Location of the study area Lichtenstein-Unterhausen in the Swabian Alb, southwest Germany (Thiebes et al., 2012).

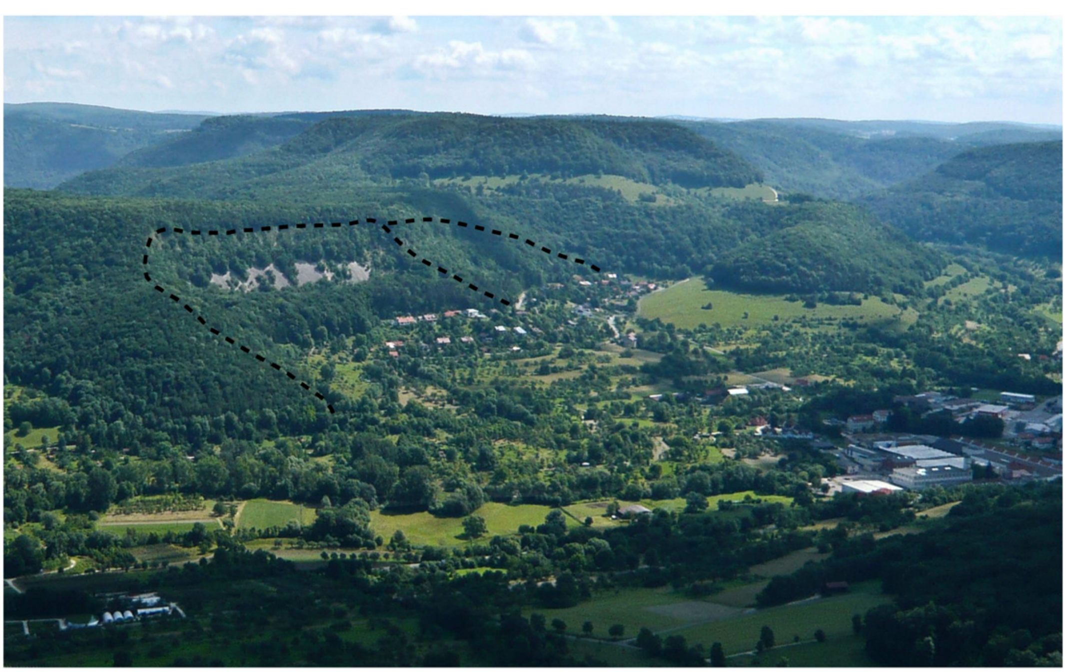

Fig. 2. Photo of the main landslide bodies in the study area with their assumed boundaries (photo by Benni Thiebes).

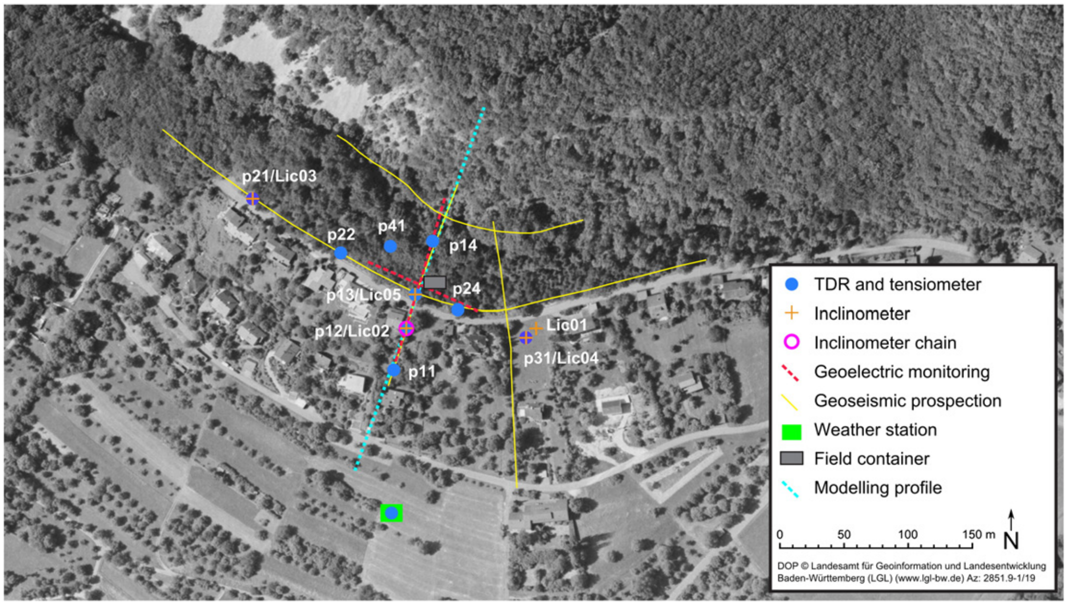

Fig. 3. Monitoring system installed by the InterRISK and ILEWS projects.

flow within each column is computed using Richards' (1931) equation with the unsaturated conductivity being defined by the Millington and Quirk (1959) procedure. Flow between columns is simulated using the Darcy (1856) equation for saturated flow. At each major iteration of the simulation the calculated positive and negative pore water pressures are incorporated directly into a stability model using Bishop's (1955) simplified circular method to yield a Factor of Safety (FoS). CHASM contains a search routine to locate the shear surface with the lowest FoS at each time step of the simulation. CHASM is also capable of integrating the effects of for example vegetation, three-dimensional topography, stabilisation measures and seismicity on slope stability, however, the respective extensions where not used within this study. Additional information, including derivation of the equations applied in CHASM is available elsewhere (Anderson and Richards, 1987; Anderson and Thallapally, 1996; Anderson et al., 1996; Collison and Anderson, 1996; Wilkinson et al., 2000, 2002a, 2002b).

3.2. Input data requirements

To apply CHASM and integrate it into a WebGIS application, requires the following input data: a slope model describing the material layers in the subsurface and their geotechnical characteristics, groundwater conditions, rainfall scenarios and the definition of an automated shear surface search procedure.

The slope model used for CHASM simulation was compiled from several data sources including geological maps, drillings and geophysical surveys. Four material types were accounted for in the slope stability modelling using CHASM; Upper Jurassic limestone, Middle Jurassic marl, the limestone scree present in the head scarp area of the large landslide body, and the superficial regolith (slope debris) covering most of the study area. The upper and lower limits of the Upper and Middle Jurassic were extracted from the available geological maps (1:25,000 and 1:50,000), neglecting the reported tilt of these lithological units by 1–2° (Leser, 1982). The spatial extent of the limestone scree slope was mapped on a digital orthophoto, and the thickness was estimated based on the geoelectric resistivity measurements by Kruse (2006).

The estimation of the thickness of slope debris was based on drillings, seismic refraction prospection (refer to Fig. 3 for positions of the profiles), topographic analysis of landslide deposits and spatial interpolation.

In total, five drillings of moderate depths (8–16 m) were performed by the ILEWS project (refer to Fig. 3 for positions of the boreholes); however, only one drilling (Lic02) reached the intact bedrock. By assuming that the seismic characteristics of the bedrock at Lic02 are representative for the all seismic profiles, the thickness of slope debris was assessed for the entire area covered by the seismic survey. For areas of the landslide deposits which had not been analysed by seismic refraction, e.g. the lower section of the larger landslide body, an iterative approach using a topographic analysis was utilised. In a first step, the landslide boundaries were connected by a TIN-triangulation in order to simulate the undisturbed slope conditions. However, the preliminary results were inadequate and were subsequently improved by a separate TIN-triangulation of the eastern and western landslide bodies. To further increase the quality of the debris estimation, a topographic analysis of the landslide deposits was carried out on the digital terrain model (DTM) with a 1 m resolution. Several profiles were drawn across the boundaries of the landslide bodies, and the thickness of the deposits were estimated based on the difference in elevation and expert knowledge. For areas which are undisturbed by landslide activity, additional drillings described by Ohmert et al. (1988) were used to estimate the thickness of the slope debris. In total, 14 drillings had been carried out in close vicinity of the study area, and were consequently used to determine the bedrock for similar relative topographic positions. In order to ensure a smooth interpolation of slope debris thickness for the entire study area, some additional points with estimated bedrock depths had to be created. The final interpolation utilised the tension spline routine in ArcGIS.

To be able to carry out stability simulations with CHASM, the layers of the subsurface model had to be related to geotechnical parameters. These include effective angle of internal friction, effective cohesion, hydraulic conductivity, saturated and unsaturated bulk density, saturated moisture content, and suction moisture curves for each considered lithological unit. In this study, the respective parameter values were adopted from the study of Thiebes (2012), who carried out extensive CHASM modelling and sensitivity analyses for a single slope profile in the same study area.

Groundwater conditions were derived from analysis of the hydrological monitoring system (see Fig. 3). The annual minimum and maximum groundwater tables were assessed from tensiometer measurements, which provide the relative position of the groundwater by the recorded excess pore water pressure (UMS, 2007). To establish a realistic groundwater table interpolation over the entire study area, some additional groundwater levels were calculated by spatial interpolation in ArcGIS using the Inverse Distance Weighting routine.

Rainfall scenarios in the study were applied from the KOSTRA atlas (Bartels et al., 2005; Malitz, 2005) developed by the German Weather Service (DWD). KOSTRA is based on a complex statistical regionalisation of local station precipitation data between 1951 and 2000, and provides rainfall intensities for event durations between 5 minutes and 72 hours, as well as annual occurrence probabilities from 0.5 and 100 years. KOSTRA was used to generate rainfall scenarios of storm durations between 1 and 72 hours, annual occurrence probabilities between 1 and 100 years, and three rainfall intensity distributions. In addition, three types of rainfall scenarios were distinguished, i.e. normal, maximum intensity and worst case scenarios. Normal scenarios were based on KOSTRA default settings for determination of rainfall intensities. For maximum intensity scenarios, KOSTRA default settings were increased to the maximum of the permitted range (4 to 12% more total rainfall depending on annual occurrence probability and storm duration). The worst case scenarios also include the tolerance range which is advised if model outputs are to be used for planning purposes. Total rainfall for these scenarios is between 10% and 20% higher than in normal scenarios.

Two automated shear surface search routines for circular shear surfaces (Bishop's method) were developed to effectively focus CHASM calculations on the profile sections most likely to experience instability. The basis for the shear surface searches was a geometrical procedure provided by Anderson (2009, personal communication), which was modified to better fit slope conditions in the study area. The shear surface search routine includes rules for the positioning of the centre of potential slip circles as well as the incremental increase of the search radius between iterations. For profiles with a length of 400 m or less, the centre of potential shear surfaces can be located at 50% profile length. For longer profiles, the potential centre of slip circles is located at one third of the profile length. The search procedures were excessively tested and calibrated on various slope profiles with varying lengths.

3.3. Integration into WebGIS

The CHASM decision-support system was designed with a web frontend and a server backend. The web frontend is implemented as a Java web-application and the user guidance utilises the open source JavaScript framework Qooxdoo. In addition, the JavaScript library OpenLayers is utilised to display and interact with the map. The server backend consists of a webserver, a map server, a Postgres data base for the management of input parameters and simulation results, and the WPS service which essentially runs CHASM. In this study, the WPS specifications of version 1.0.0 (Schut, 2007) were used.

4. Results

4.1. Input data generation

Following the previously described methodology, the four-layered subsurface model was generated with a spatial resolution of 2 m (Figure 4). All the Middle Jurassic stratum is completely covered by other material and is not exposed to the surface. The Upper Jurassic limestone only has some few outcrops located above the limestone scree, and is otherwise covered by slope debris. The spatial interpolation of debris thickness yielded average values between 13 and 16 m for the landslide deposit, with a maximum depth of over 20 m. For undisturbed slope sections, debris accumulations between 1 and 6 m were estimated. Debris thickness thereby increases from the plateau areas to the lower slope sections. The limestone scree in the upper section of the slope was assessed to have a maximum thickness of approximately 8 m. Since it was assumed that the scree slope had developed after the initial landslide event, the scree material only covers the surface and is not buried below the slope debris.

The determination of minimum and maximum groundwater tables primarily utilised the shallow and medium depth tensiometers which were saturated and measured excess pore water pressure during some time of the year. The resulting groundwater levels vary between 1.3 m and 2 m for the wet periods, and 3.7 m to 6 m during drier phases. The results of spatial interpolation were assessed to be adequate for the areas of the study area that can be assumed to be most likely influenced by slope failures.

A total number of 180 rainfall scenarios were created with total rainfall ranging from 18 mm to 144 mm for a 1 hour normal scenario rainfall (1 in 1 year probability) and a 72 hour rainfall worst case scenario (1 in 100 years probability), respectively. The maximum hourly intensity reaches 70 mm in the worst-case scenario for a 1 hour rainfall with a return period of 100 years.

The developed shear surface search routine effectively concentrates the search procedure on the upper slope areas, which are assumed most likely to be influenced by potential landslide initiation — reflecting potential reactivation of at least parts of the landslide deposits. In order to increase the modelling speed the number of potential shear surfaces analysed was limited in the search procedure. The developed procedure reduces the number of possible shear surface positions by a relatively large radius increment of Bishop's shear circles, while at the same time allowing for a high number of possible positions in a horizontal direction. Retrogressive slope failures involving the massive Upper Jurassic limestone can also be modelled, however, they were not given priority in this work. Four sample profiles are displayed in Fig. 5.

4.2. CHASM decision-support system

The integration of CHASM into the WebGIS resulted in a simple-to-use system (Figure 6) with the capability of generating a range of user-friendly screens for each application (Figure 7). The slope profile for which stability is to be calculated can be selected by clicking the desired start and end-points on the displayer map (Figure 7-1). The profile for the CHASM simulation is automatically generated by a Java Advanced Imaging (JAI) routine which detects the properties of the subsurface model. Depending on the profile length, the most appropriate shear surface search algorithm is selected. In the next step (Figure 7-2), the user can enter a name for the model run and set simulation length and iteration period. Additional choices include the scenarios for rainfall and groundwater table, as well as soil characteristics. In its current state, all rainfall scenarios derived from KOSTRA can be selected for slope stability calculation from a drop down menu (Figure 7-3), and two groundwater levels, i.e. annual minimum and maximum are available. For soil characteristics, either the CHASM standard parameter or the parameter values given by Thiebes (2012) can be chosen. The selected parameters are exported to the data base and stored under the profile name. Subsequently, the WPS initiates the CHASM simulation which typically has a run time of approximately one minute (Figure 7-4). The selected slope profile is colour-coded according to the simulated FoS of the last hour of the simulation, with green for a FoS greater than 1.3, orange for a FoS between 1.0 and 1.3, and red for a FoS below 1.0 (Figure 7-5). Further information, such as the development of the FoS throughout the simulation or the position of the shear surface can be accessed for previously executed model runs (Figure 7-6). Sample results are presented in Fig. 7-7 and 7-8, in which the rainfall period is displayed in blue, and the FoS is shown as a green line. Fig. 7-7 shows the FoS a decreasing over the first hours of the simulation as adjustments in slope hydrology take place following the “cold” model start. During rainfall, the FoS continues to steadily decrease until reaching an “equilibrium” value of approximately 1.45. Fig. 7-8 illustrates the FoS simulation results of a rainfall event which shows marked fall in FoS values caused

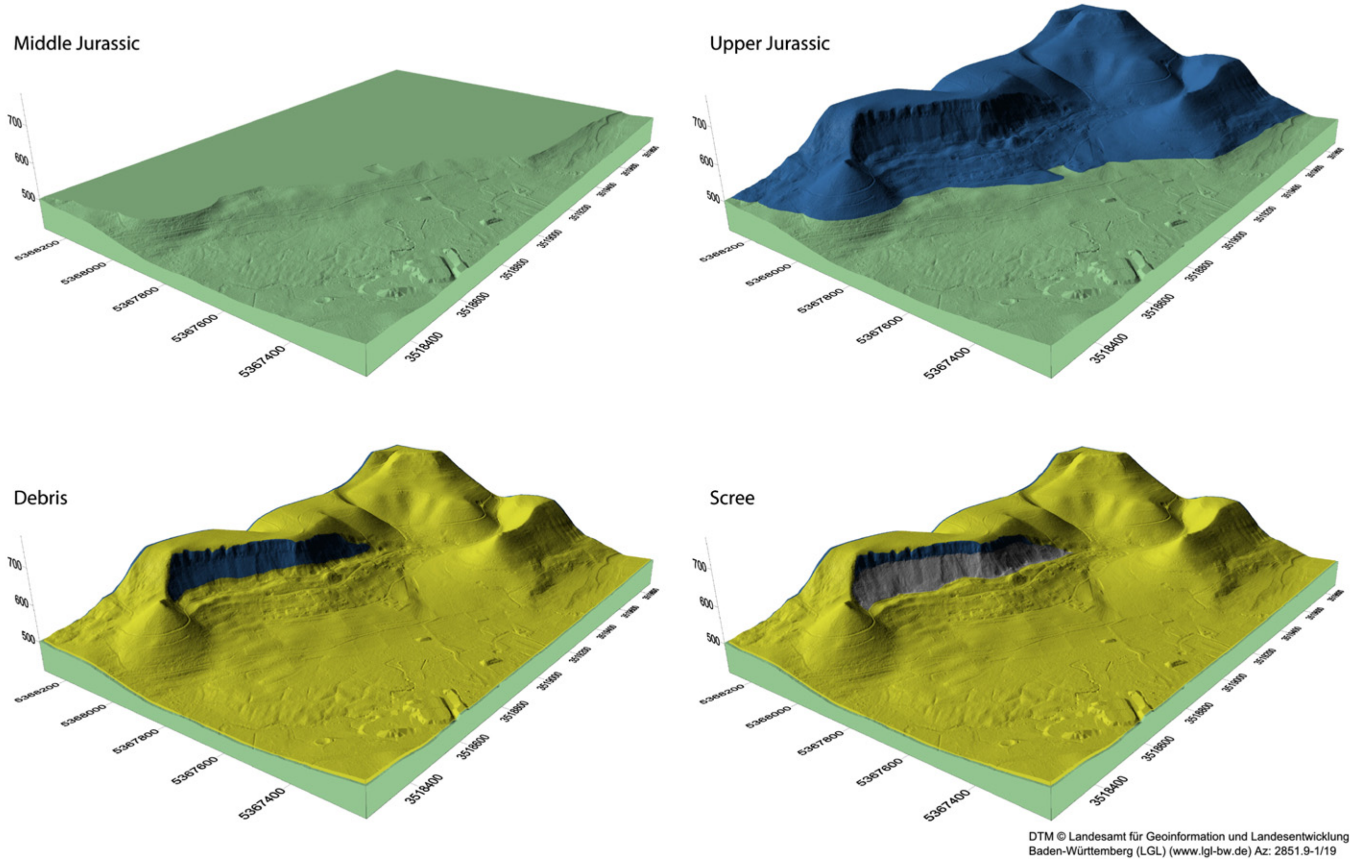

Fig. 4. Subsurface model.

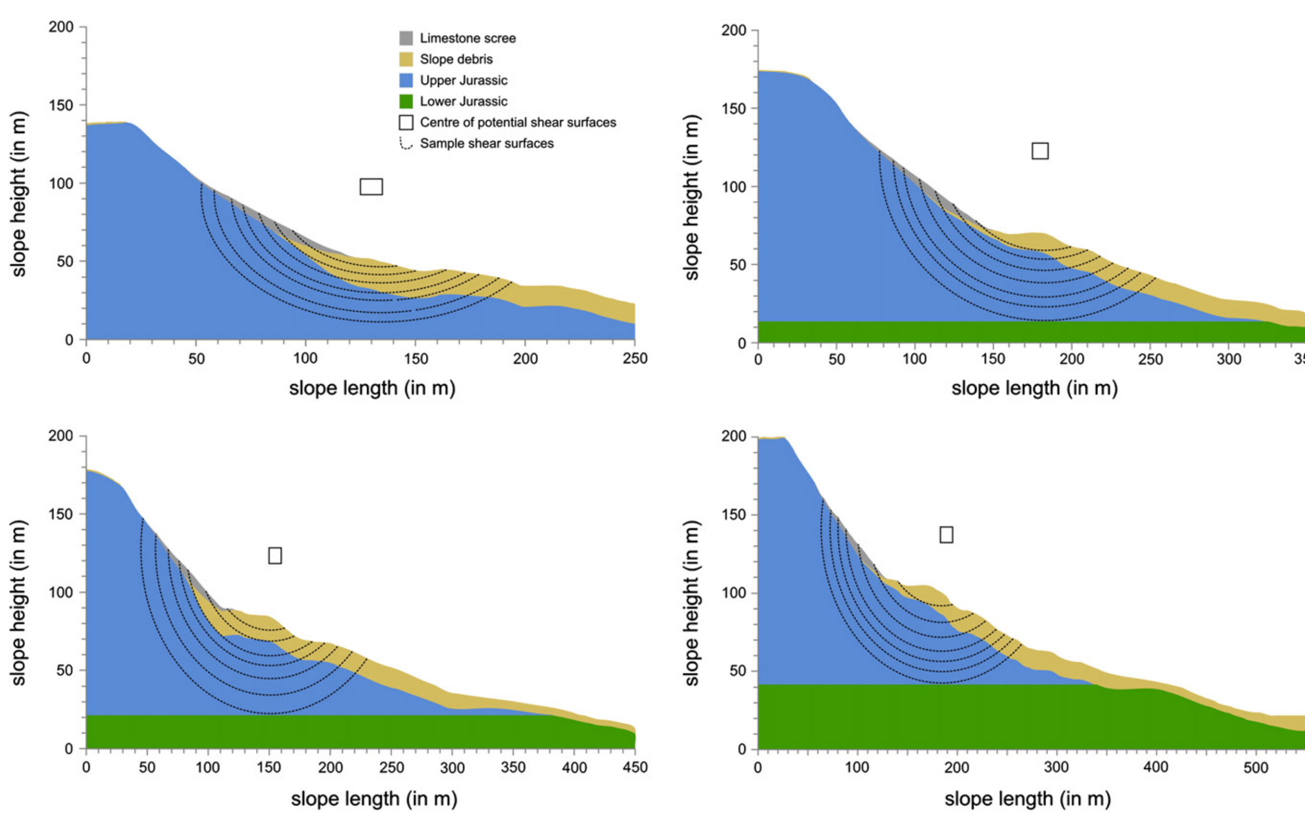

Fig. 5. Potential shear surfaces for four sample profiles.

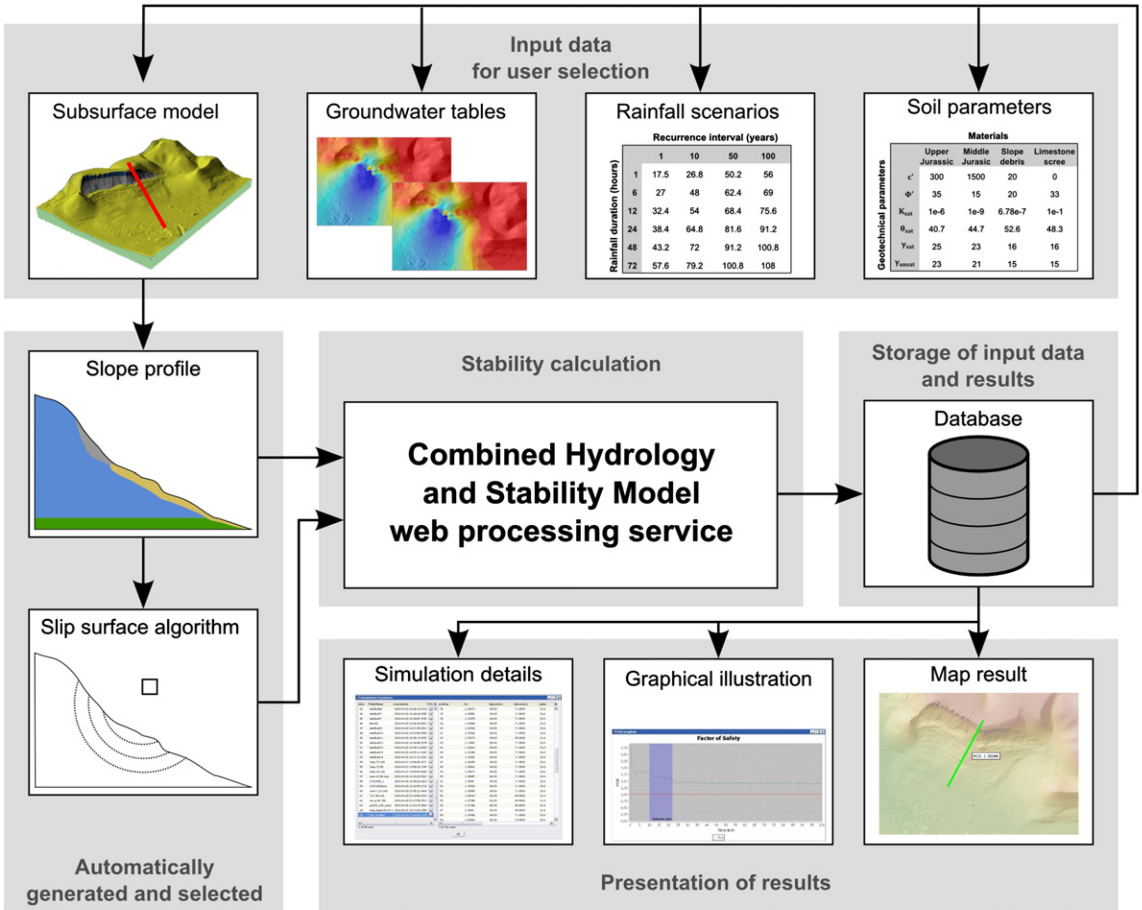

Fig. 6. Flowchart of the CHASM decision-support system.

by changes in the position of critical shear surfaces. Finally, instead of generating a new profile for each simulation, it is also possible to select previously simulated profiles from the database.

The CHASM decision-support application is available to registered users and can be used in German and English language. In addition, a bilingual step-by-step tutorial explaining the functionality of the service and the basic terms of slope stability calculation were developed to increase usability.

5. Discussion

Inevitably, uncertainties are inherent in the presented CHASM decision-support system which also derives from the estimation of subsurface conditions, geotechnical characteristics and groundwater tables; and the influence of spatial interpolation. The determination of the spatial extent of subsurface materials utilised a variety of input data to create a high quality representation of the underground conditions. In particular seismic refraction demonstrated to provide cost and time efficient data source. The assessment of groundwater levels relied on the extensive hydrological monitoring system. However, the estimation of groundwater scenarios proved to be difficult due to sometimes contradicting measurements and the complex subsurface hydrology which features preferential flow paths. Even though spatial interpolation of debris thickness and groundwater levels involved uncertainties, the data for the main landslide-affected area can be assumed to have relatively high reliability.

The automated shear surface search algorithm integrated into the web-based decision-support system is an efficient, and systematic procedure for identifying the most significant potential failure surfaces. However, there is a trade-off between accuracy of modelling results and the simulation run times. The implemented algorithm allows for a wide range of shear surface positions in a horizontal direction, but restricts the number of slip surfaces searches in a vertical direction, thereby reducing overall model run times. As expected, some simulation runs illustrate significant temporal shifts in the FoS. Such shifts represent changes in the critical shear surface caused by pore water pressure changes demonstrating the importance of the conjoint inclusion of automatic slip search and dynamic pore pressure modelling. It is therefore apparent that the implemented CHASM decision-support system facilitates rapid limit-equilibrium slope stability analysis for various slope profiles, and is transferable to other study areas with similar slope morphologies.

6. Conclusions

This study presents the integration of limit-equilibrium model CHASM into a web-based GIS. The implemented decision-support system allows for the quick application of CHASM to freely selectable slope profiles without the need to elaborate the slope profile and shear surface definition files. A wide selection of input data such as rainfall scenarios and soil characteristics, and model parameters can be chosen by the user. It was not the goal of this study to convert the entire CHASM stability software into a web-based simulation programme but rather to enhance the model flexibility and to investigate the benefits of an integration of standard slope stability software into a WebGIS. Nevertheless, the entire system was designed to be adaptable and could be upgraded to integrate other CHASM features.

The implemented CHASM decision-support system utilises open-source software and was developed according to OGC standards which are important condition for the interoperability of the system

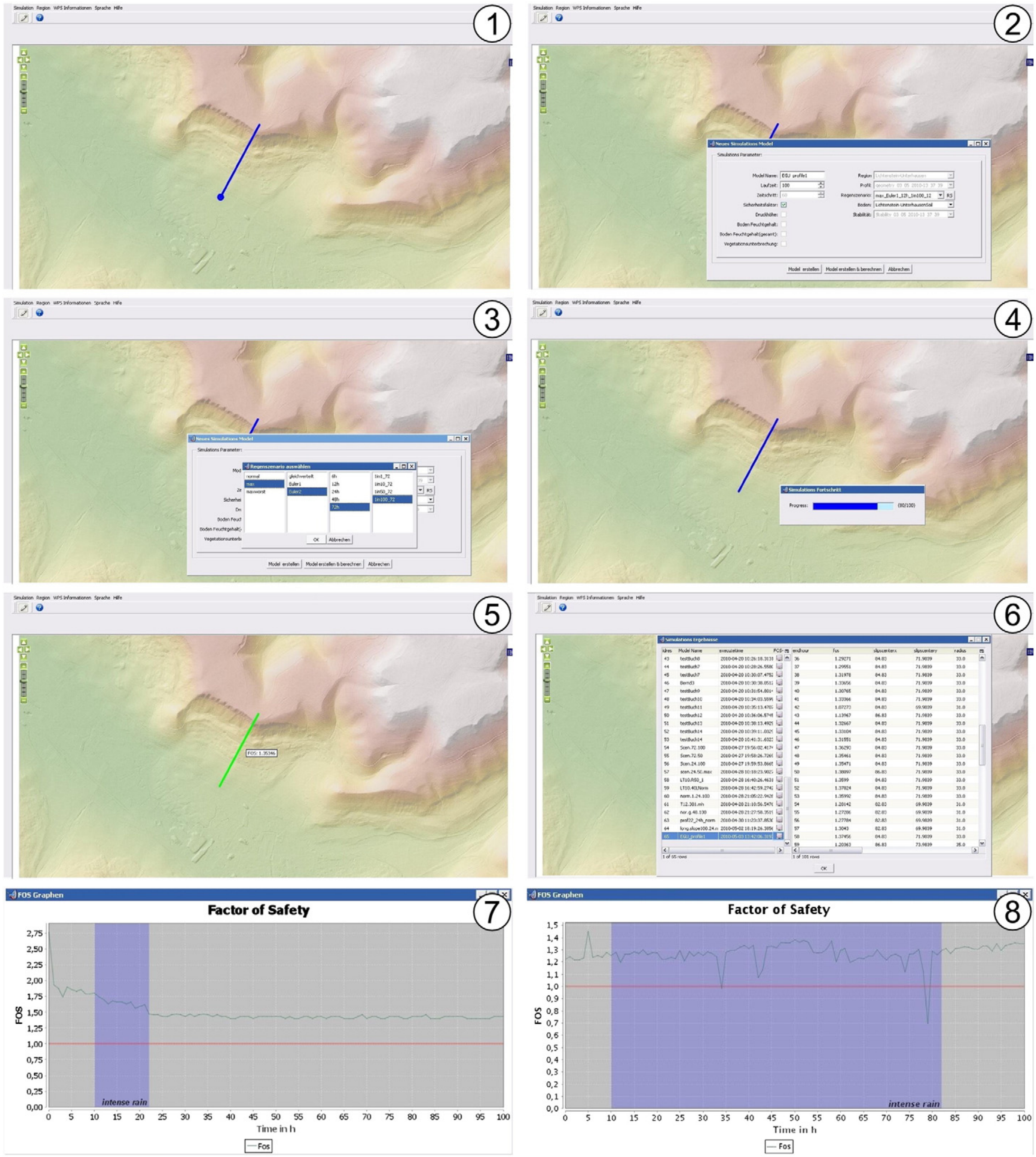

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Fig. 7. Sample application screenshots of the decision-support system.

components, and the transferability of the system as a whole. The implementation of CHASM as a WPS shows the potential of this service to integrate complex simulation algorithms into web-based geospatial applications. However, to fully take advantage of the WPS capabilities it would be useful to integrate these into general purpose GIS software.

The CHASM decision-support system represents an innovative prototype which demonstrates a new approach to landslide modelling within GIS, and confirms the technical feasibility of undertaking a physically-based slope stability analysis within web-based GIS. The flexible and time-efficient application allows for quick judgment of slope stability which will be helpful for stakeholders and decisionmakers who require to assess slope stability situation for large areas in a short time.

It can be expected that future endeavours in the field of landslide hazard management will utilise similar approaches and that the integration of designated landslide simulation models into GIS environments will increase. Further research in this field should additionally integrate real-time hydrological monitoring data, thereby extending the system's usability to early warning applications, and more comprehensive risk management.

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References

Abramson, L.W., 2002. Slope Stability and Stabilization Methods. John Wiley and Sons, New York (744 pp.).

Anderson, M.G., Richards, K., 1987. Modelling slope stability: the complementary nature of geotechnical and geomorphological approaches. In: Anderson, M.G. (Ed.), Slope Stability: Geotechnical Engineering and Geomorphology. John Wiley & Sons Ltd., Chichester, pp. 1–9.

Anderson, S.A., Thallapally, L.K., 1996. Hydrologic response of a steep tropical slope to heavy rainfall. In: Senneset, K. (Ed.), Landslides. 7th International Symposium on Landslides. Balkema, Rotterdam, Trondheim, Norway, pp. 1489–1495.

Anderson, M.G., Lloyd, D.M., Park, A., Hartshorne, J., Hargraves, S., Othman, A., 1996. Establishing new design dynamic modelling criteria for tropical cut slopes. In: Senneset, K. (Ed.), Landslides. 7th International Symposium on Landslides. Balkema, Rotterdam, Trondheim, Norway, pp. 1067–1072.

Anderson, M., Holcombe, L., Flory, R., Renaud, J.-P., 2008. Implementing low-cost landslide risk reduction: a pilot study in unplanned housing areas of the Caribbean. Natural Hazards 47 (3), 297–315.

Barla, G., Amici, R., Vai, L., Vanni, A., 2004. Investigation, monitoring and modelling of a landslide in porphyry in a public safety perspective. In: Lacerda, W., Ehrlich, M., Fontoura, S.A.B., Sayao, A.S. (Eds.), Landslides: Evaluation and Stabilization. 9th International Symposium on Landslides. A.A. Balkema Publishers, Leiden, Rio de Janeiro, Brazil, pp. 623–628.

Bartels, H., Dietzer, B., Malitz, G., Albrecht, F.M., Guttenberg, J., 2005. KOSTRA-DWD-2000. Starkniederschlagshöhen für Deutschland (1951–2000). Fortschreibungsbericht. Deutscher Wetterdienst (DWD).Abteilung Hydrometeorologie, Offenbach, Germany (53 pp.).

Bell, R., 2007. Lokale und regionale Gefahren- und Risikoanalyse gravitativer Massenbewegungen an der Schwäbischen Alb. University of Bonn, Germany (305 pp.).

Bell, R., Kruse, J.-E., Garcia, A., Glade, T., Hördt, A., 2006. Subsurface investigations of landslides using geophysical methods — geoelectrical applications in the Swabian Alb (Germany). Geographica Helvetica 3, 201–208.

Bell, R., Mayer, J., Pohl, J., Greiving, S., Glade, T. (Eds.), 2010. Integrative Frühwarnsysteme für Gravitative Massenbewegungen (ILEWS) — Monitoring, Modellierung, Implementierung. Klartext, Essen, Germany (272 pp., in German).

Bibus, E., 1986. Die Rutschung am Hirschkopf bei Mössingen (Schwäbische Alb). Geowissenschaftliche Rahmenbedingungen — Geoökologische Folgen. Geoökodynamik (7), 333–360 (in German).

Bibus, E., 1999. Vorzeitige, rezente und potentielle Massenbewegungen in SW-Deutschland — Synthese des Tübinger Beitrags zum MABIS-Projekt. In: Bibus, E., Terhorst, B. (Eds.), Angewandte Studien zu Massenbewegungen, Tübinger Geowissenschaftliche Arbeiten, pp. 1–57 (in German).

Bishop, A.W., 1955. The use of the slip circle in the stability analysis of slopes. Geotechnique 5 (1), 7–17.

Bleich, K.E., 1960. Das Alter des Albtraufs. Jahreshefte des Vereins für Vaterländische Naturkunde in Württemberg 115, 39–92 (in German).

Cannata, M., Luan, T.X., Molinari, M.E., Long, N.H., 2010. WPS application for shallow landslide hazard assessment. GeoInformatics for Spatial-Infrastructure Development in Earth and Allied Sciences (GIS-IDEAS) 2010 (http://wgrass.media.osaka-cu.ac.jp/gisideas10/viewabstract.php?id = 391 [Accessed: 9 March 2012]).

Chung, C., 2008. Predicting landslides for risk analysis — spatial models tested by a cross-validation technique. Geomorphology 94 (3–4), 438–452.

Collison, A.J.C., Anderson, M.G., 1996. Using a combined slope hydrology/stability model to identify suitable conditions for landslide prevention by vegetation in the humid tropics. Earth Surface Processes and Landforms 21 (8), 737–747.

Coulomb, C.A., 1776. Essai sur une application des regles des maximis et minimis a quelques problemes de statique relatifs a l'architecture. Memoires de l'Academie Royale pres Divers Savants 7, 343–387 (in French).

Darcy, H., 1856. Les fontaines publiques de la ville de Dijon. Victor Dalmont, Paris, France (647 pp., in French).

Dietrich, W.E., Real de Asua, R., Coyle1, J., Orr, B., Trso, M., 1998. A validation study of the shallow slope stability model, SHALSTAB, in forested lands of Northern California. Stillwater Ecosystem, Watershed & Riverine Sciences, Berkley, USA (59 pp.).

Ferentinou, M.D., Sakellariou, M., Matziaris, V., Charalambous, S., 2006. An Introduced methodology for estimating landslide hazard for seismic and rainfall induced landslides in a geographical information system environment. In: Nadim, F., Pöttler, R., Einstein, H., Klapperich, H., Kramer, S. (Eds.), Geohazards, Proceedings of the ECI Conference on Geohazards. Lillehammer, Norway, pp. 1–8.

Fundinger, A., 1985. Ingenieurgeologische Untersuchung und geologische Kartierung (Dogger/Malm) der näheren Umgebung der Rutschungen am Hirschkopf bei Mössingen und am Irrenberg bei Thanheim (Baden-Würrtemberg), Diplomarbeit. Geowissenschaftliche Fakultät, University Tübingen, Germany, 125 pp. (in German)

Goetz, J.N., Guthrie, R.H., Brenning, A., 2011. Integrating physical and empirical landslide susceptibility models using generalized additive models. Geomorphology 129 (3–4), 376–386.

Guzzetti, F., Reichenbach, P., Cardinali, M., Galli, M., Ardizzone, F., 2005. Probabilistic landslide hazard assessment at the basin scale. Geomorphology 72 (1–4), 272–299.

Hennrich, K., Crozier, M.J., 2004. A hillslope hydrology approach for catchment-scale slope stability analysis. Earth Surf. Process. Landforms 29 (5), 599–610.

Iovine, G.G.R., Lollino, P., Gariano, S.L., Terranova, O.G., 2010. Coupling limit equilibrium analyses and real-time monitoring to refine a landslide surveillance system in Calabria (southern Italy). Natural Hazards and Earth System Science 10 (11), 2341–2354.

Janbu, N., 1996. Slope stability evaluations in engineering practice. In: Senneset, K. (Ed.), Landslides. 7th International Symposium on Landslides. Balkema, Rotterdam, Trondheim, Norway, pp. 17–34.

Kallinich, J., 1999. Verbreitung, Alter und Ursachen von Massenverlagerungen an der Schwäbischen Alb auf der Grundlage von geomorphologischen Kartierungen. In: Bibus, E., Terhorst, B. (Eds.), Angewandte Studien zu Massenbewegungen, Tübinger Geowissenschaftliche Arbeiten, pp. 59–82 (in German).

Keersmaekers, R., Maertens, J., Van Gemert, D., Haelterman, K., 2008. Modeling landslide triggering in layered soils. In: Chen, Z.-Y., Zhang, J.-M., Ho, K. (Eds.), Landslides and Engineered Slopes: From the Past to the Future, Proceedings of the 10th International Symposium on Landslides and Engineered Slopes. Taylor & Francis, Xi'an, China, pp. 761–767.

Krauter, E., 1992. Hangrutschungen — ein Umweltproblem. Ingenieurvermessung'92. XI. Internationaler Kurs für Ingenieurvermessung. Dümmler, Bonn, Zürich, Switzerland, in German, pp. 1–12.

Kruse, J.E., 2006. Untergrunderkundung und Monitoring von gravitativen Massenbewegungen mit Gleichstromgeoelektrik und Radiomagnetotellurik. University of Bonn, Germany (151 pp., in German).

Lateh, H., Anderson, M.G., Ahmad, F., 2008. CHASM — the model to predict stability of gully walls along the east-west highway in Malaysia: a case study. Proceeding of The First World Landslide Forum. ISDR, Tokyo, Japan, pp. 340–343.

Leser, H., 1982. Erläuterungen zur Geomorphologischen Karte 1:25,000 der Bundesrepublik Deutschland. GMK 25 Blatt 9 7520 Mössingen Geomorphologische Detailkartierung in der Bundesrepublik Deutschland. Geo Center, Stuttgart, Germany. (in German)

Malitz, G., 2005. KOSTRA-DWD-2000. Starkniederschlagshöhen für Deutschland (1951–2000). Grundlagenbericht. Deutscher Wetterdienst (DWD), Hydrometeorologie, Offenbach, Germany. (32 pp., in German).

Matziaris, V.G., Ferentinou, M., Sakellariou, M.G., 2005. Slope stability in unsaturated soils under static and rainfall conditions. Ovidius University Annals Series: Civil Engineering 1 (7), 103–110.

Meyenfeld, H., 2009. Modellierungen seismisch ausgelöster gravitativer Massenbewegungen für die Schwäbische Alb und den Raum Bonn und Erstellen von Gefahrenhinweiskarten, Dissertation. University of Bonn, Germany, 241 pp. http://hss.ulb.uni-bonn.de/2009/1692/1692.htm (in German).

Millington, R.J., Quirk, J.P., 1959. Permeability of porous media. Nature 183, 387–388.

Neuhäuser, B., Terhorst, B., 2007. Landslide susceptibility assessment using 'weights-of-evidence' applied to a study area at the Jurassic escarpment (SW-Germany). Geomorphology 86 (1–2), 12–24.

Ohmert, W., Von Koenigswald, W., Münzing, K., Villinger, E., 1988. Geologische Karte 1:25.000 von Baden Württemberg. Erläuterungen zu Blatt 7521 Reutlingen. Geologisches Landesamt Baden-Württemberg, Freiburg. (in German).

Pack, R.T., Tarboton, D.G., Goodwin, C.N., Prasad, A., 2005. SINMAP 2 — A Stability Index Approach to Terrain Stability Hazard Mapping, SINMAP User Manual 2.00 (73 pp.).

Papathoma-Köhle, M., Neuhäuser, B., Ratzinger, K., Wenzel, H., Dominey-Howes, D., 2007. Elements at risk as a framework for assessing the vulnerability of communities to landslides. Natural Hazards and Earth System Science 7 (6), 765–779.

Petley, D.N., Mantovani, F., Bulmer, M.H., Zannoni, A., 2005. The use of surface monitoring data for the interpretation of landslide movement patterns. Geomorphology 66 (1–4), 133–147.

Price, D.G., Freitas, M.H.D., 2009. Engineering Geology: Principles and Practice. Springer (459 pp.).

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. Physics 1 (5), 318–333.

Rossi, M., Guzzetti, F., Reichenbach, P., Mondini, A.C., Peruccacci, S., 2010. Optimal landslide susceptibility zonation based on multiple forecasts. Geomorphology 114 (3), 129–142.

Sakellariou, M., Ferentinou, M., Charalambous, S., 2006. An integrated tool for seismic induced landslide hazards mapping. In: Agioutantis, Z., Komnitsas, K. (Eds.), First European Conference on Earthquake Engineering and Seismology, Proceedings of the joint event of 13th ECEE & 30th General Assembly of the ESC. Geneva, Switzerland, pp. 1365–1375.

Schädel, K., Stober, I., 1988. Rezente Großrutschungen an der Schwäbischen Alb. Jahreshefte des Geologischen Landesamtes Baden-Württemberg 30, 431–439 (in German).

Schut, P., 2007. OpenGIS Web Processing Service: OGC 05-007r7: Version 1.0. 0. Open Geospatial Consortium Inc.(A. Quelltexte 68).

Spickermann, A., Schanz, T., Datcheva, M., 2003. Numerical study of a potential landslide in the Swiss Alps. In: Aifantis, E.C. (Ed.), 5th EUROMECH Solid Mechanics Conference. Thessaloniki, Greece, pp. 17–22.

Terhorst, B., 1997. Formenschatz, Alter und Ursachenkomplexe von Massenverlagerungen an der schwäbischen Juraschichtstufe unter besonderer Berücksichtigung von Boden- und Deckschichtenentwicklung. Tübinger Geowissenschaftliche Arbeiten, Reihe D2 Geographisches Institut, Tübingen, Germany (212 pp., in German).

Terzaghi, K., 1925. Erdbaumechanik auf bodenphysikalischer Grundlage. F. Deuticke, Vienna, Austria (in German).

Thiebes, B., 2012. Landslide Analysis and Early Warning Systems: Local and Regional Case Study in the Swabian Alb. Springer, Germany (266 pp.).

Thiebes, B., Bell, R., Glade, T., 2012. Landslide analysis and integrative early warning — local and regional case studies. In: Eberhardt, E., Froese, C.R., Turner, A.K., Leroueil, S. (Eds.), Proceedings of the 11th International & 2nd North American Symposium on Landslides. Presented at the Landslides and Engineered Slopes — Protecting Society through Improved Understanding. Taylor & Francis, London, pp. 1915–1921.

Tinti, S., Manucci, A., 2008. A new computational method based on the minimum lithostatic deviation (MLD) principle to analyse slope stability in the frame of the 2-D limit-equilibrium theory. Nat. Hazards Earth Syst. Sci 8, 671–683.

Turner, A.K., 1996. Socioeconomic significance of landslides. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides: Investigation and Mitigation (Special Report). Transportation Research Board, pp. 12–35.

UMS, 2007. Bedienungsanleitung T8 Langzeitmonitoring-Tensiometer. UMS GmbH, München 56 pp. (in German).

Wilkinson, P.L., Brooks, S.M., Anderson, M.G., 2000. Design and application of an automated non-circular slip surface search within a combined hydrology and stability model (CHASM). Hydrological Processes 14 (11–12), 2003–2017.

Wilkinson, P.L., Anderson, M.G., Lloyd, D.M., 2002a. An integrated hydrological model for rain-induced landslide prediction. Earth Surface Processes and Landforms 27 (12), 1285–1297.

Wilkinson, P.L., Anderson, M.G., Lloyd, D.M., Renaud, J.P., 2002b. Landslide hazard and bioengineering: towards providing improved decision support through integrated numerical model development. Environmental Modelling & Software 17 (4), 333–344.

Xie, M., Esaki, T., Cai, M., 2004a. A GIS-based method for locating the critical 3D slip surface in a slope. Computers and Geotechnics 31 (4), 267–277.

Xie, M., Esaki, T., Zhou, G., 2004b. GIS-based probabilistic mapping of landslide hazard using a three-dimensional deterministic model. Natural Hazards 33 (2), 265–282.

Xie, M., Esaki, T., Cai, M., 2006. GIS-based implementation of three-dimensional limit equilibrium approach of slope stability. Journal of Geotechnical and Geoenvironmental Engineering 132 (5), 656–660.

Yin, Y., 2009. Landslide mitigation strategy and implementation in China. In: Sassa, K., Canuti, P. (Eds.), Landslides-Disaster Risk Reduction. Springer, Berlin, Germany, pp. 482–484.

Zhao, P., Lu, F., Foerster, T., 2012. Towards a geoprocessing web. Computers & Geosciences 47, 1–2.