Hydrogeological mapping in Switzerland

Marc Schürch · Ronald Kozel · Laurent Jemelin

Abstract The 1:500,000 geological, tectonic and hydrogeological maps of Switzerland have been updated using a new approach for a geographical information system (GIS). Geological, tectonic and hydrogeological data are combined in a single polygon data set. Specific data (point and line elements) are additionally represented on a separate GIS layer for each map respectively. The new 1:500,000 hydrogeological map of Switzerland consists of two different sheets. The first sheet provides information on the near-surface groundwater resources and qualitative estimates of their yield. The second sheet displays the groundwater resource vulnerability and the capacity of lateral contaminant transport. The 1:100,000 hydrogeological map of Switzerland shows the distribution and use of groundwater in a selected area. The near-surface consolidated and unconsolidated rocks are classified in this map according to their permeability and lithological and petrographical properties. The map is available as a pixel map.

Résumé Les cartes aux 1:500,000 de la Suisse, portant sur la géologie, la tectonique et l'hydrogéologie, ont été mises à jour en utilisant une nouvelle approche pour un système d'information géographique (GIS, en anglais). Les données géologiques, tectoniques et hydrogéologiques ont été combinées sur un seul set de polygones. Les données plus spécifiques (points et lignes) sont représentées dans une couverture séparée, pour chaque carte respectivement. La nouvelle carte hydrogéologique de Suisse au 1:500,000 est constituée de deux différentes feuilles. La première feuille apporte des informations sur les ressources proches de la surface et sur leur rendement. La seconde feuille montre la vulnérabilité des ressources souterraines et le risque de pollution par transport latéral. La carte hydrogéologique de Suisse au 1:100,000 montre la distribution et l'utilisation de l'eau souterraine dans la région sélectionnée. Les roches consolidées ou meubles de sub-surface, sont classées au regard de leur perméabilité et de leurs propriétés lithologique et pétrographique. La carte est disponible pixellisée.

Resumen Los mapas geológico, tectónico e hidrogeológico de Suiza a escala 1:500,000 han sido actualizados utilizando un nuevo enfoque para un sistema de información geográfico (SIG). Los datos geológicos, tectónicos e hidrogeológicos se combinan en un conjunto de datos en un solo polígono. Por otra parte, para cada uno de los mapas, los datos específicos (elementos puntuales y lineales) se representaron en una capa separa del SIG. El nuevo mapa hidrogeológico de Suiza a escala 1:500,000 contiene dos capas diferentes. La primera de ellas suministra información de los recursos hídricos subterráneos poco profundos y estimaciones cualitativas de sus rendimientos. La segunda capa muestra la vulnerabilidad de este recurso y el riesgo debido al transporte lateral de contaminantes. El mapa hidrogeológico de Suiza a escala 1:100,000 muestra la distribución y uso del agua subterránea en un área seleccionada. Los sedimentos consolidados y no consolidados cercanos a la superficie se clasifican en este mapa en función de su permeabilidad y propiedades litológicas y petrográficas. El mapa se encuentra disponible como un mapa de pixeles.

Keywords Mapping · Groundwater management · Scale effects · Geographic information systems · Switzerland

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Introduction

The 1:500,000 and 1:100,000 scale hydrogeological maps of Switzerland are presented, as well as the development of a geographic information system (GIS) with a combined approach for the 1:500,000 geological, tectonic and hydrogeological maps. Furthermore, the report summarizes how the hydrogeological maps of different scales are

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Table 1 Advantages and disadvantages of conventional maps compared to digital hydrogeological maps

	Conventional hydrogeological map	Digital hydrogeological map
Theme	Rigid representation limited to a specific theme (geological formation or tectonics, etc.) that was chosen prior to mapping	Possibility of interactively choosing different themes (stratigraphy, tectonics, lithology, etc.) and possibility to optimize the choice
Application	Visual interpretation of the printed map	Possibility of changing the extent and scale of the selected map area
	Simple handling in the field	Possibility of combining the geological information with other themes (area development planning, water protection, etc.)
	General overview, project planning, surface water–groundwater interaction studies	Hazard management (floods, landslides, earthquakes)
Updating and reprint	The map is used for several decades until it is updated and reprinted	The map can be continuously updated with the latest data
		The user can always obtain the most up-to-date map
Print	The map is printed in high quality, which is relatively expensive	A few copies can be printed for each selected map area
	A print run of a few thousand copies for each sheet	Prints can be produced to meet specific user requirements (map area, requests, choice of information)

applied by federal and cantonal authorities, as well as by geological and engineering companies in Switzerland.

Hydrogeological maps provide information on major groundwater resources, groundwater flow, recharge and discharge zones, groundwater/surface-water interactions, the location of important springs and pumping wells, vulnerability of the groundwater resources, the distribution of areas with low permeability protective cover, as well as areas with multi-layered aquifers and surface drainage systems. United Nations Educational, Scientific, and Cultural Organization (1984) describe an international legend for hydrogeological maps. Also, United Nations Educational, Scientific, and Cultural Organization (2004) show a groundwater resources map of the world. In general, hydrogeological maps contain different hydrogeological information, depending on the purpose for which they have been developed. Consequently, a wide range of types of hydrogeological maps exist, including maps of aquifer permeability, groundwater resources and aquifer yield, groundwater vulnerability, groundwater levels, groundwater flow direction, groundwater protection, location of springs, tracer test results, and groundwater chemistry (Novoselova 2004). Table 1 summarizes the advantages and disadvantages of conventional and digital hydrogeological maps.

More than 80% of Swiss drinking water requirements are met by groundwater (water supply wells and springs). Half of these groundwater resources are provided by the very productive sequences of gravel in extensive river valleys that cover about 6% of Switzerland's land surface (Spreafico and Weingartner 2005). Aquifers composed of these gravel sequences are predominantly fed by infiltrat-

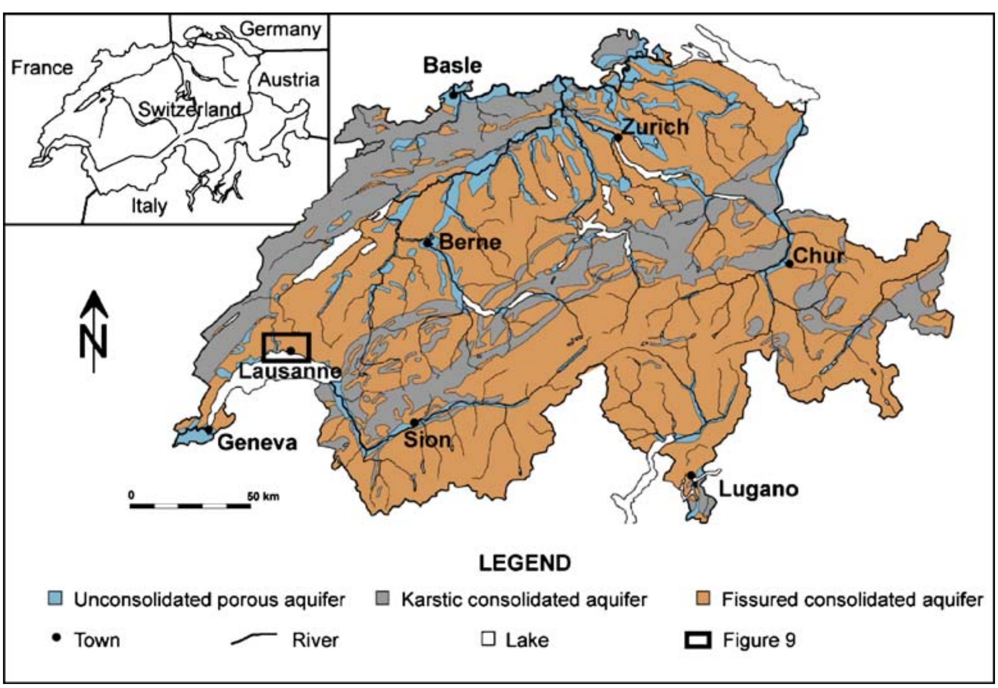

Fig. 1 1:2,200,000 hydrogeological map showing main aquifer types in Switzerland (after Dupasquier and Parriaux 2002)

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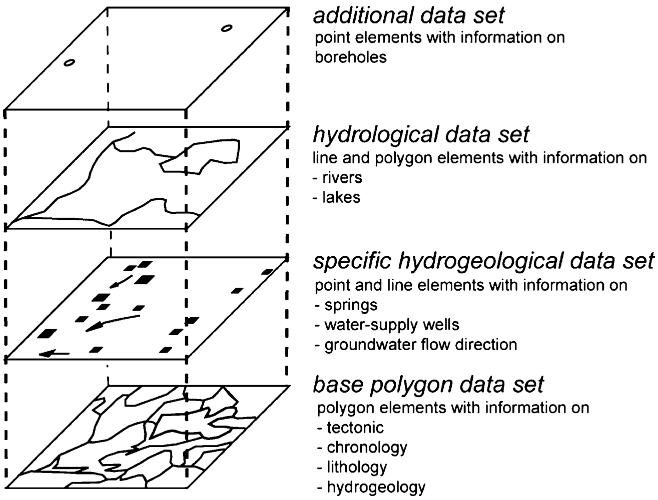

Fig. 2 Structure of the digital database for the 1:500,000 hydrogeological map

ing river water and are characterized by a high capacity for removing pollutants (Swiss Agency for the Environment, Forests, and Landscapes and Federal Office for Water and Geology 2004). Carbonate rocks with significant subsurface drainage systems (about 16% of the Swiss land surface) dominate in the Jura region in the northwestern part of Switzerland, as well as in the northern part of the Alps (see Fig. 1). These karst uplands are water poor at the surface but very productive springs are present. Such spring systems are highly susceptible to all types of pollution. Tertiary Molasse sandstones, conglomerates, Quaternary gravel moraines, crystalline rocks, and flysch cover about 78% of the Swiss land surface. In these regions, groundwater extraction is limited to small but locally significant springs, which are typical of low productivity aquifers (Kilchmann et al. 2004). Rock types associated with negligible groundwater resources are widespread throughout Switzerland and mostly represent aquicludes. In the Jura region, these aquicludes are characterized by clay-rich strata, whereas on the Swiss Plateau, they are mainly marly Molasse deposits and Quaternary clayey silts. Aquicludes in Alpine regions are composed of sedimentary and metamorphic rock sequences. Small-sized springs emanate from these rocks (Bitterli et al. 2004).

The 1:500,000 digital hydrogeological map of Switzerland

The GIS "1:500,000 digital geological maps of Switzerland"

In 1994, the Swiss Geological Survey initiated a project to update the 1:500,000 geological, tectonic, and hydrogeological maps of Switzerland and to incorporate them into a digital GIS (Heitzmann and Philipp 1999). In this GIS, the geological, tectonic, and hydrogeological data are combined in one single data set (polygon elements). This approach for the GIS differs from the conventional approach where a polygon data set for each map is composed. The 1:500,000 digital geological, tectonic, and hydrogeological maps of Switzerland were developed from the same base polygons and together constitute a GIS. The base polygons were digitalized for the 1:500,000 geological map of Switzerland. These polygons were then used as a database for the realization of the tectonic and hydrogeological maps. Though these polygons may have been split into sub-polygons, where necessary, for the tectonic and hydrogeological maps; their boundaries have been respected. The base polygons were then adapted in an appropriate manner so that they correspond to both polygons of the tectonic and hydrogeological maps.

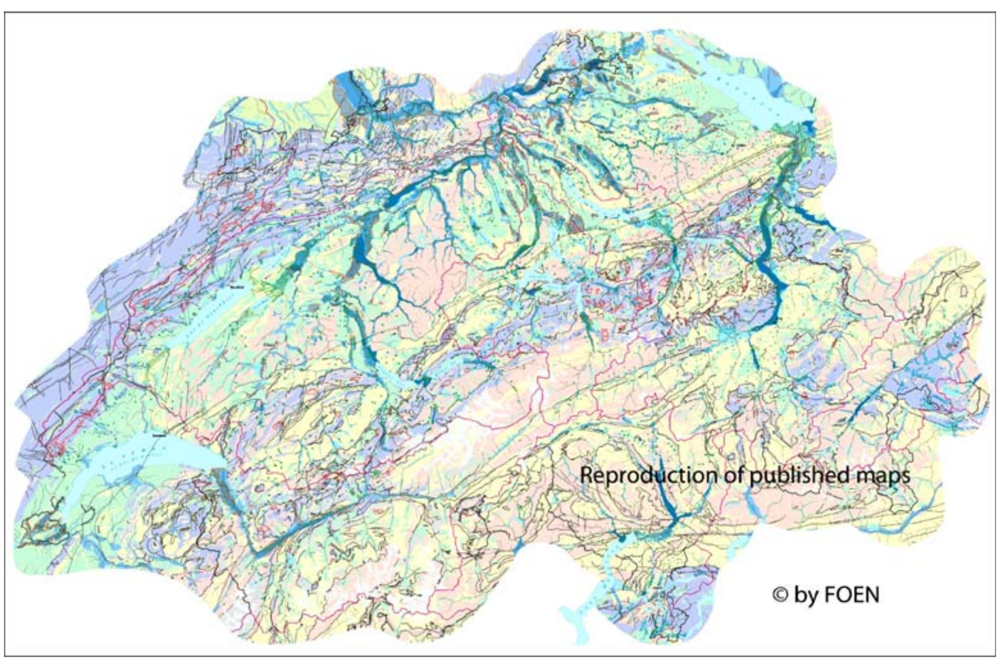

Fig. 3 The 1:500,000 hydrogeological map of Switzerland, groundwater resources sheet (after Bitterli et al. 2004). Reproduced with permission of Federal Office for the Environment FOEN

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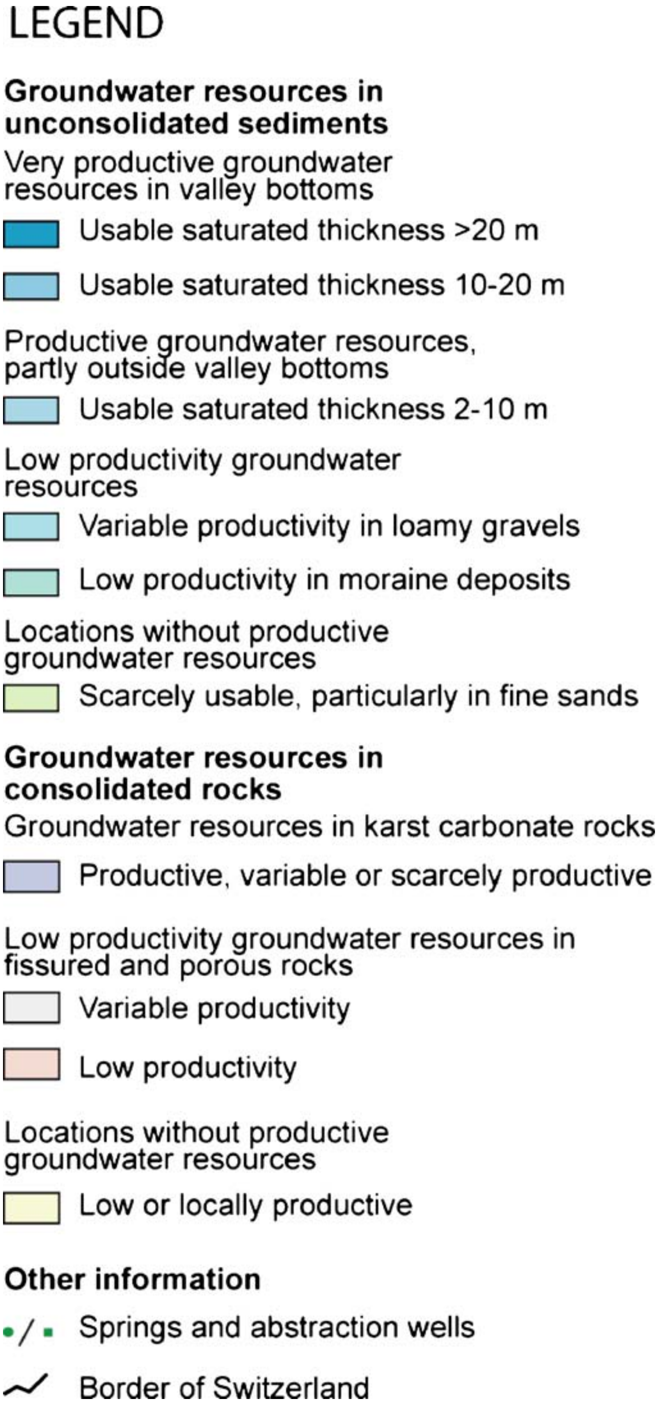

Fig. 4 Legend of the 1:500,000 hydrogeological map of Switzerland, groundwater resources sheet (after Bitterli et al. 2004)

Specific data (point and line elements) for each map were added on separate GIS layers. The GIS of the 1:500,000 geological, tectonic, and hydrogeological maps of Switzerland has the following structure:

- A single data set containing the polygons for geology, tectonics, and hydrogeology
- A tectonic layer representing faults, thrusts, and nappes
- A hydrogeological data set containing important springs, groundwater supply wells, surface drainage systems, groundwater levels, and aquifer boundaries, as well as recharge and discharge areas
- A layer representing geomorphologic features such as landslides, rock fall, alluvial fans, drumlins, and moraines
- A layer containing the distribution of boreholes
- An additional hydrological layer containing rivers and lakes

The 1:500,000 geological, tectonic, and hydrogeological maps of Switzerland were published between 2004 and 2006 (Bitterli et al. 2004; Federal Office for Water and Geology 2005a,b). The timescale for setting up the GIS of the 1:500,000 geological, tectonic, and hydrogeological maps of Switzerland was approximately 10 years with total costs of about US $1.3 million.

The 1:500,000 digital hydrogeological map of Switzerland, groundwater resources sheet

The 1:500,000 hydrogeological map of Switzerland is the first hydrogeological map of this country that provides qualitative estimates of the yield of different aquifer types (unconsolidated porous aquifer, karstic consolidated aquifer, and fissured consolidated aquifer). This approach for hydrogeological mapping is different from the conventional approach that represents the permeability of different rock types. The 1:500,000 groundwater resources sheet shows the location and extent of near-surface groundwater resources, recharge and discharge areas, the location of principal water supply wells and springs, significant deep groundwater resources, and groundwater flow direction. The map reflects the close relation among geology, surface water, and groundwater.

Data acquisition and hydrogeological mapping were carried out by four regional private geological companies. One of these companies managed the project and compiled the specific regional information into a nationwide map. A specialized private contractor developed the digital database. The Swiss Geological Survey coordinated the project. Data acquisition and hydrogeological mapping carried out by the regional geological companies enabled additional local hydrogeological knowledge to be integrated into the map. Nonetheless, in order to guarantee a uniform representation of the hydrogeological information on a national scale, the coordination office had to ensure that the various regional companies adhered strictly to the guidelines describing the methods and procedures to be used in the hydrogeological mapping. These methods and procedures had previously been tested for a selected area. The project coordinator carried out the test phase. The test case provided significant information that permitted optimization of the methods and procedures used for the implementation phase.

The implementation phase of the project consisted of the following steps: data acquisition, drafting of preliminary maps, drafting of maps with specific information

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Table 2 Comparison between the productivity type of groundwater resources for the 1:500,000 hydrogeological map of Switzerland, groundwater resources sheet and the rock permeability type for the 1:100,000 hydrogeological map of Switzerland

Scale	1:500,000	1:100,000
Hydrogeological map type	Groundwater resources productivity	Rock permeability
Class	Unconsolidated sediments	Unconsolidated sediments
	Very productive groundwater resources in valley bottoms, usable saturated thickness >10 m	High permeability gravels in valley bottoms Moderate permeability sandy gravel in valley bottoms
	Productive groundwater resources, partially outside valley bottoms, usable saturated thickness 2–10 m	High permeability gravel at the periphery of valley bottoms or with low river water infiltration Moderate permeability sandy gravel in valley bottoms High permeability gravel outside valley bottoms
	Low productivity groundwater resources in loamy gravel and in moraine deposits	Variable permeability loamy gravel and moraine deposits Moderate to low permeability loamy and gravel-poor scree deposits
	Locations without productive groundwater resources	Low to very low permeability fine sands, silts, and loam
	Consolidated rocks	Consolidated rocks
	Productive, variable or low productivity groundwater resources in karstic carbonate rocks	High permeability karstic carbonate rocks
	Variable and low productivity groundwater resources in fissured and porous rocks	Variable permeability sediments and crystalline rocks
	Locations without productive groundwater resources	Low to very low permeability loamy schists and mica schists
GIS system	Vector map	Pixel map

(both maps were 1:200,000), digitalization, compilation, generalization of the data from the 1:200,000 working scale to the final 1:500,000 map scale and corrections. On the preliminary map, the digital base polygons were assigned with hydrogeological elements (type of the groundwater resources, see Fig. 2). The specific information relating to groundwater recharge and discharge areas, groundwater flow directions, deep aquifers, as well as groundwater quality were entered on a separate map. Highly productive and productive groundwater resources beneath low permeability protective cover, which were not represented in the digital data set of the geological map, were added to the base data set polygons. The simultaneous representation of the groundwater resource (the main element of the digital hydrogeological map) and of its low permeability protective cover (main element of the digital geological map) could be managed in the database with an additional second hydrogeological code. In areas without low permeability protective cover, both codes have the same number.

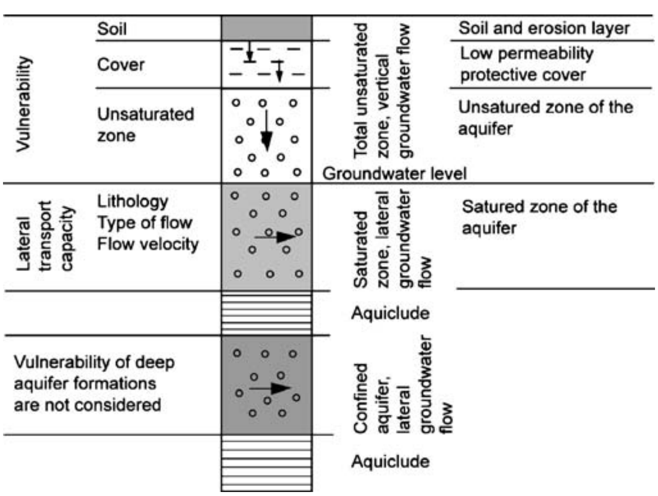

Fig. 5 Schematic cross-section of groundwater resources in unconsolidated sediments and properties used to calculate the vulnerability and the lateral transport capacity

Figures 3 and 4 show the groundwater resources sheet and the legend of the 1:500,000 hydrogeological map of Switzerland respectively and, in particular, the different types of the productivity of the groundwater resources. Productivities are classified according to the main aquifer type (Bitterli et al. 2004). The most productive groundwater resources are in coarse-grained unconsolidated porous deposits. Within this “very productive” type of groundwater resource (principally gravel in river valleys), the productivity or yield is differentiated, principally on the basis of the thickness of the saturated zone (usable saturated thickness). The permeability, lithology, and hydraulic connection to surface waters are other factors that are taken into account. Gravel at the periphery and outside of the valley bottom areas may also have high permeability and a substantial thickness. However, these deposits are often largely unsaturated. As a result, these deposits are only classified as “productive”. Groundwater resources in moraine deposits and in fine- to medium-grained scree deposits are generally classified in the “low productivity” category. Locations without any productive groundwater resources in unconsolidated sediments are associated with clay, silt, fine sands, or areas with protective covers of relatively low permeability. However, whereas some high-yielding springs occur in karst regions, these areas do not have the productivity of the extensive alluvial valley gravel. Fissured, occasionally porous types of hard rock may contain variable to low productivity groundwater resources. Table 2 shows a comparison between the productivity types of groundwater resources for the 1:500,000 hydrogeological map of

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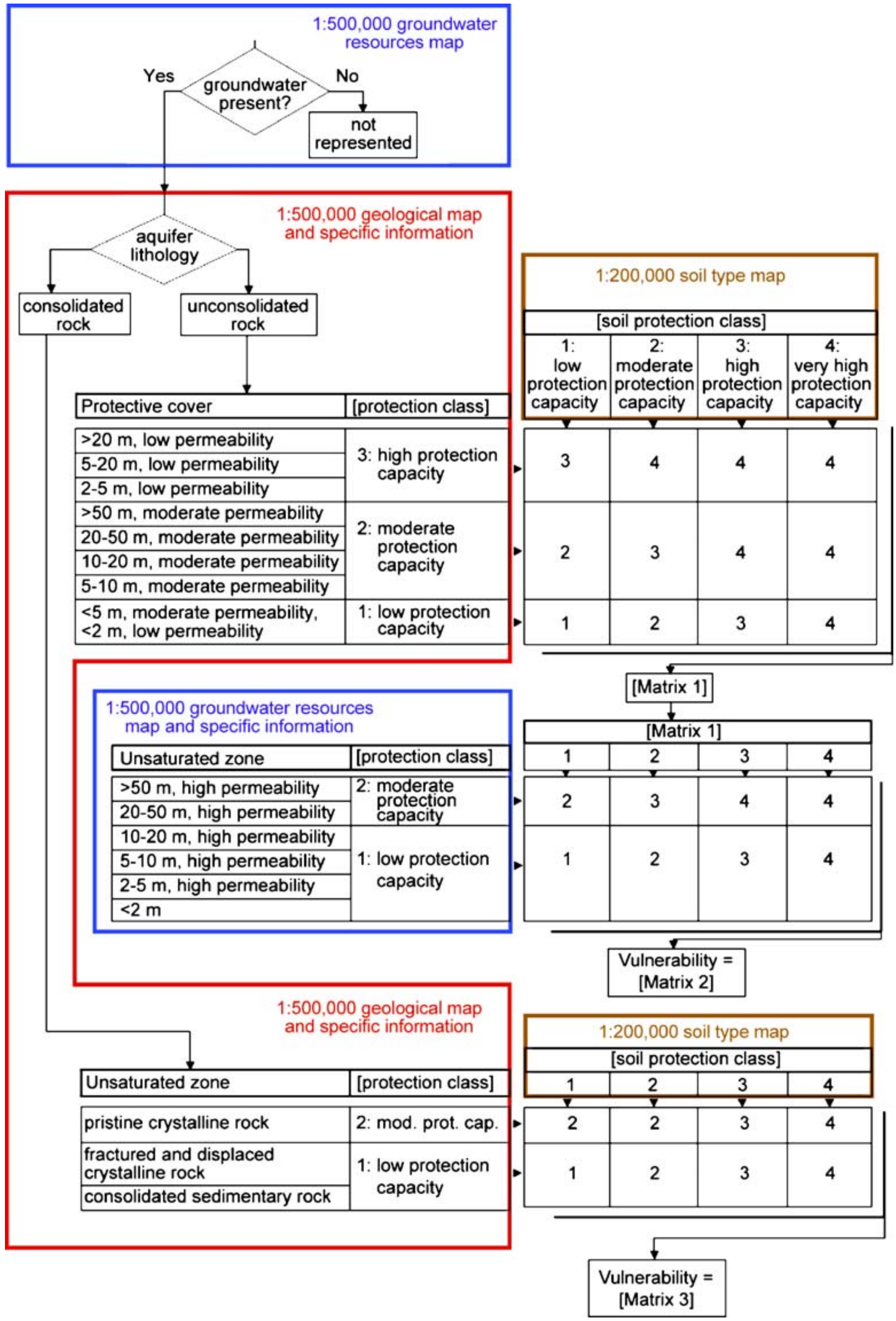

Fig. 6 Model used to determine groundwater vulnerability at a national scale

Switzerland and the rock permeability type for the 1:100,000 hydrogeological map of Switzerland.

The 1:500,000 digital hydrogeological map of Switzerland, groundwater vulnerability sheet

The project organization for the groundwater vulnerability sheet of the 1:500,000 hydrogeological map of Switzerland is similar to that of the groundwater resources sheet. The complexity of the groundwater vulnerability map and associated quality management necessitated a scientific group composed of experts from universities and governmental agencies who consulted and reviewed the map during its development. Guidelines, which were tested in three selected areas, facilitated data acquisition and mapping and guaranteed a uniform representation of the vulnerability nationwide.

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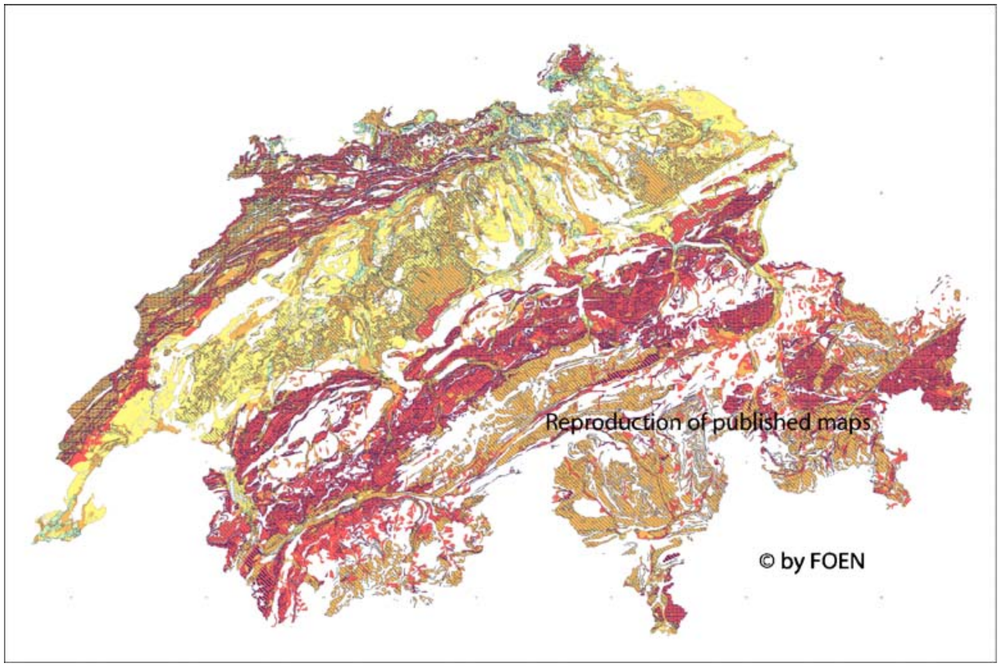

Fig. 7 The 1:500,000 hydrogeological map of Switzerland, groundwater vulnerability sheet. Reproduced with permission of the Federal Office for the Environment FOEN

Two kinds of vulnerability are generally considered in vulnerability mapping (Zwahlen 2004):

1. An intrinsic vulnerability which simply expresses the sensitivity to natural and human impacts of the transfer zone between ground surface and the water table throughout the unsaturated zone
2. The weighting of the intrinsic vulnerability with the hazard probability (for example a pollution emission), which depends on demography, industrial or agricultural activities, and the local distribution of roads and railways, provides a risk map

Vulnerability cannot be measured directly, but is determined using geological and hydrogeological data and the sensitivity of an aquifer to point and diffuse human contamination.

Vulnerability maps can be compiled at different scales (Vrba and Zaporozec 1994). For example, Lobo-Ferreira and Oliveira (1997) have applied the DRASTIC methodology at a national scale in Portugal. In Switzerland, a practical guide for determination of groundwater protection zones based on vulnerability mapping at local and regional scale has been developed in both karstic regions (Swiss Agency for the Environment, Forests, and Landscapes 2000) and in areas underlain by fissured rock aquifers (Pochon and Zwahlen 2003). The concept for the development of the vulnerability sheet of the 1:500,000 hydrogeological map of Switzerland was developed in the mid 1990s. The first step in vulnerability assessment involved evaluation of the protection capacity of the soil, the low permeability protective cover, as well as the unsaturated zone. In the second step, the lateral transport capacity of the saturated zone was determined. Figure 5 schematically presents a cross-section of unconsolidated sediments and their properties, which were used to determine the vulnerability and the lateral transport capacity.

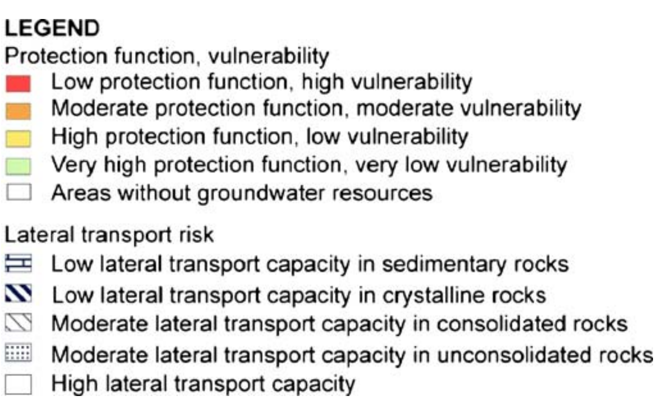

Fig. 8 Legend of the 1:500,000 hydrogeological map of Switzerland, groundwater vulnerability sheet

From the 1:200,000 digital soil type map, the soil protection capacity was calculated by taking into account the soil thickness and water-storage capacity. From the 1:500,000 digital geological and hydrogeological maps of Switzerland and from specific additional information, the protection capacity was determined for both protective cover and unsaturated zone. Figure 6 shows the model that was used to determine the groundwater vulnerability on the 1:500,000 hydrogeological map of Switzerland. The vulnerability of unconsolidated sediments was calculated by taking into account the protection capacity of the soil, protective cover, and unsaturated zone. For consolidated rocks, the concept generally applies a low protection capacity for the underground with one exception: a moderate protection capacity for pristine crystalline rock to account for its low permeability.

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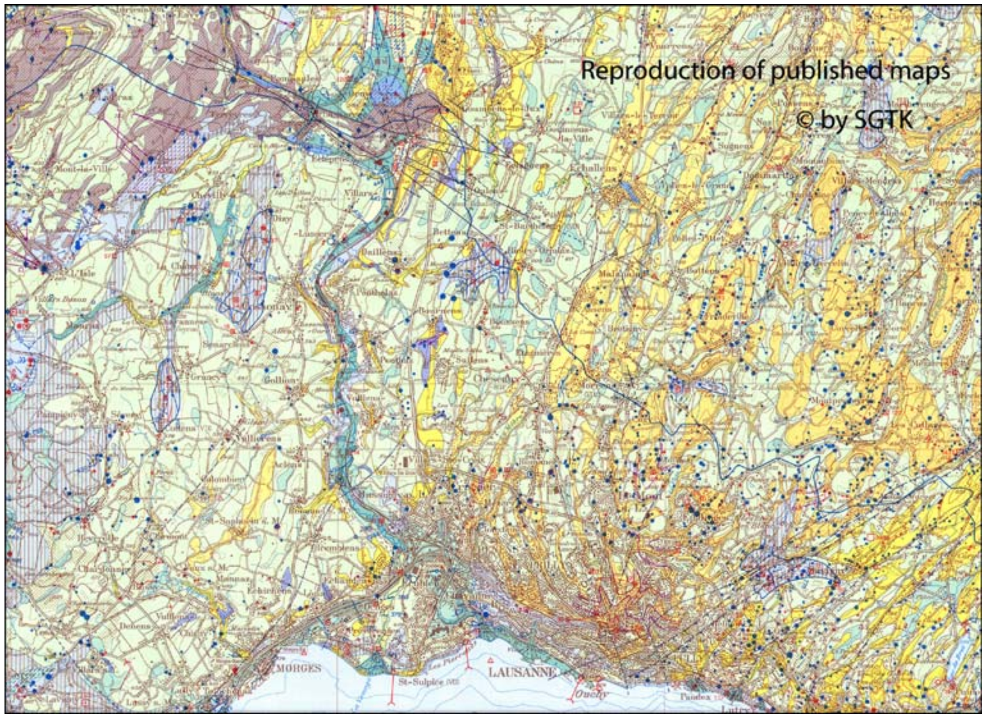

Fig. 9 Section of the 1:100,000 hydrogeological map of Switzerland, Vallorbe Geneva North sheet (Pasquier et al. 2006). Reproduced with permission of Swiss Geotechnical Commission SGTK

Determination of the lateral transport capacity was achieved via conversion of the "type of groundwater resources" and "type of circulation" elements from the 1:500,000 groundwater resources map. Figure 7 shows the 1:500,000 groundwater vulnerability map of Switzerland and Fig. 8 its legend.

The 1:100,000 hydrogeological map of Switzerland

H. Jäckli submitted the first sheet of the 1:100,000 hydrogeological map of Switzerland to the Swiss Geotechnical Commission and the Swiss Geological Commission in 1966. Both commissions decided to publish the map because of its important scientific value. H. Jäckli and T. Kempf subsequently developed the concept for the map for a selected area in the north-central part of Switzerland. The map was published with an explanatory note providing a hydrogeological overview of the area and site-specific examples with details of lithology, groundwater quality, groundwater level data, groundwater balance, cross-sections, and a reference list (Jäckli and Kempf 1972). This map has served as a model for mapping hydrogeological information and for mapping groundwater resources and their exploitation in particular. Six other sheets with explanatory notes have, subsequently, been produced under the direction of the Swiss Geotechnical Commission (Kempf 1980; Jäckli et al. 1985; Pfirter and Hauber 1991; Haering et al. 1993; Pasquier et al. 1999, 2006). An additional sheet is in preparation for the region around Basle.

The 1:100,000 maps show the near-surface consolidated and unconsolidated rocks classified according to their permeability and lithological and petrographical properties.

Table 3 Addresses for ordering the different hydrogeological maps of Switzerland discussed in this report

Hydrogeological map	Address for ordering
Map series Geo500 of the Swiss Geological Survey, 1:500,000 geological, tectonic and hydrogeological map of Switzerland:	Federal Office of Topography Swisstopo
GIS database and paper copy	Swiss Geological Survey Seftigenstrasse 264 3084 Wabern Switzerland http://www.swisstopo.ch
Hydrological atlas of Switzerland, 1:500,000 hydrogeological map of Switzerland, groundwater resources sheet and vulnerability sheet:	Federal Office for the Environment FOEN
Paper copy (including map, geological synthetic cross-sections and explanatory note)	Swiss Hydrological Survey 3003 Bern Switzerland http://hydrant.unibe.ch/hades/hades_en.htm
1:100,000 hydrogeological map of Switzerland:	Swiss Geotechnical Commission SGTK
Paper copy (including map and explanatory note)	ETH-Zentrum, CAB E 77 Universitätsstrasse 6 8092 Zürich Switzerland http://www.sgtk.ch
1:2,200,000 hydrogeological sketch of Switzerland:	Federal Office for the Environment FOEN
Paper copy A6	Swiss Hydrological Survey Hydrogeology Section 3003 Bern Switzerland http://www.environment-switzerland.ch

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Hydrologically effective structures such as thrusts, faults, synclines, and anticlines, as well as dipping of rock beds are represented in an illustrative fashion. Groundwater flow direction, isohyetals of mean groundwater level, as well as recharge and discharge areas and areas with multi-layered aquifers are also specifically represented. Other symbols show the location of springs, abstraction wells, hydrologically important boreholes, and karstic features (swallow holes, polje, karst conduits, and springs). Figure 9 shows a section of the 1:100,000 hydrogeological map of Switzerland, Vallorbe Geneva North sheet.

The 1:100,000 hydrogeological maps were initiated by the Swiss Geotechnical Commission and published with financial support by the Swiss Geological Survey and the cantons concerned. Data acquisition and hydrogeological mapping were carried out by regional private geological companies or by the Swiss Geotechnical Commission in close collaboration with experts from universities, cantons and the Swiss Geological Survey. Until now the 1:100,000 hydrogeological maps of Switzerland have been published in the conventional manner, as paper copies, but they will be also converted into pixel maps.

Experience and future development

In Switzerland, the different hydrogeological maps (Table 3 summarizes the addresses for ordering the different hydrogeological maps of Switzerland) reflect the evolution of hydrogeological knowledge and mapping techniques, the evolution of groundwater legislation and the requirements of governmental agencies and private companies in particular for hydrogeological information. In the past, hydrogeological maps were generally used to identify areas for new groundwater catchments. Today, governmental agencies need hydrogeological information to make sociological, economical, ecological, and political decisions in particular. The combination of hydrogeological, geological, land-use and hazard maps in one GIS permit the identification of areas for urban expansion, recreation, and groundwater protection in a coordinated manner. Nevertheless, the high demand for water and the water-use restrictions in many parts of Switzerland during the drought of 2003 highlight the need to find potential sites for new groundwater catchments. The GIS of the 1:500,000 hydrogeological map of Switzerland gives general information for local environmental or groundwater projects that are generally performed by geological and engineering companies and water services on a scale greater than 1:10,000. However, because of the small scale, the GIS cannot be used for groundwater protection zone studies of distinct groundwater catchments. Initial experience indicates that it should only be used for applications on a scale smaller than 1:200,000.

Cantonal agencies use the 1:100,000 hydrogeological map of Switzerland for planning their environment and engineering tasks as well as water services, whereas municipalities rely on the map for groundwater prospecting, groundwater management, and groundwater protection. Furthermore, private companies and universities consult the map for regional and local studies, because most of the 1:50,000 or 1:25,000 cantonal “groundwater maps” and “water protection maps” focus on unconsolidated aquifers (gravel) in river valleys. As a result, these maps rarely show aquifers in fissured and karstic rocks outside river valleys.

Different scale hydrogeological maps provide differing information about groundwater points. The 1:50,000 or 1:25,000 cantonal “groundwater maps” and “water protection maps” represent local information and show all abstraction wells, groundwater protection zones, as well as the observation points of the quantitative and qualitative groundwater networks. The 1:100,000 hydrogeological map of Switzerland gives a complete regional overview, whereas the 1:500,000 hydrogeological map of Switzerland shows the hydrogeology nationwide that is based on generalized data.

The presented Swiss approach using GIS for hydrogeological maps may require more time to develop the GIS than the conventional approach, because integration of an additional thematic map into the GIS needs adaptation of the existing codes in the polygon data set. However, once the GIS is produced, its maintenance and requests combining the geological, tectonic, and hydrogeological maps are less time consuming.

The digital vulnerability data set actually still needs to be integrated into the GIS. In 2005, the Swiss Geological Survey initiated a project to integrate all 1:25,000, 1:100,000, and 1:500,000 geological, tectonic, and hydrogeological maps as pixel or vector maps into an additional GIS accessible on Internet. The database has to be linked with other digital databases containing information on soil exploitation, groundwater protection zones, tracer-test results, hazards, and groundwater observation networks.

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