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Hydrogeological overview of the Bure plateau, Ajoie, Switzerland

ATTILA KOVÁCS & PIERRE-YVES JEANNIN

Key words: Karst aquifer, flow modeling, conceptual model, combined discrete channel and continuum approach, Bure plateau, milandrine, shallow karst, GIS

ABSTRACT

This study presents a hydrogeological synthesis of the most recent data from the Bure plateau in Ajoie, canton Jura, NW Switzerland. Included is a complete reappraisal of aquifer geometry and aquifer boundaries, the delineation of catchment areas based on tracing experiments, and the evaluation of the hydraulic role of different hydrostratigraphic units. Furthermore, it presents GIS-based calculations on the mean piezometric surface, the thickness of the unsaturated zone and on the thickness of the minimum and mean saturated zones. The spatial extension of the shallow karst zone is also evaluated. A coherent conceptual model and the two-dimensional steady-state combined discrete channel and continuum type numerical model of the aquifer has been constructed.

The research site is 83 km^2 in area and is underlain by slightly folded layers of Mesozoic limestones and marls. The Bure plateau is dissected by normal faults, which form a succession of elongated horst and graben structures. The main aquifer consists of Malm limestones, with thicknesses varying between zero (eastern border) and 320 m (south-eastern regions). The aquifer is bounded from below by the Oxfordian Marls. The underlying sediments of Middle Jurassic age are considered to be hydraulically independent. The surface topography of the Oxfordian Marls reveats the periclinal termination of a wide anticline over the plateau and a syncline in the southern parts. The aquifer contains three marly intercalations. Tracing experiments prove that marl layers do not act as regional aquicludes. These experiments also allow for the division of the aquifer surface into several water catchments. Based on tracing tests and piezometric data a NW-SE oriented groundwater divide seems to extend in the regions of Porrentruy – Bure – Croix. Calculations of the average (matrix flow) and minimum (conduit flow) water tables indicate an extended shallow karst zone in the region of Boncourt – Buix – St-Dizier. The thickness of the saturated zone increases towards the extremities of the research site, being thickest in the South. The thickness of the unsaturated zone shows a large variation, reaching its maximum in the central areas.

Numerical model calculations roughly reproduce the observed hydraulic heads and mean spring discharges, they confirm current ideas about hydraulic parameters and suggest the existence of extended karst subsystems throughout the model domain

RESUME

Cette étude présente une synthèse hydrogéologique régionale de la région du plateau de Bure (Ajoie, canton du Jura, Suisse). Elle expose les résultats d'une re-évaluation complète de la géométrie et de ses conditions aux limites de l'aquifère. Une nouvelle délimitation des bassins versants, une synthèse des essais de traçage et l'évaluation du rôle hydrologique des diverses formations sont aussi proposées. L'utilisation des outils modernes (SIG) a permis d'approcher les caractéristiques régionales de la zone saturée, son épaisseur, et l'épaisseur de la zone non-saturée. Ainsi, l'extension de la zone de karst où l'écoulement est libre (non noyé) dans les conduits principaux («shallow karst») a pu être évaluée. Un modèle conceptuel ainsi qu'un modèle numérique 2D combinant un milieu discret (conduits 1D) et continu (matrice 2D) a été appliqué pour le calcul à l'échelle régionale des écoulements en régime permanent.

Le secteur de recherche s'étend sur 83 km^2. Le substratum est constitué de calcaires et marnes mésozoïques légèrement plissés. Le plateau de Bure est traversé par plusieurs failles normales, formant une succession de horst et grabens. L'aquifère principal est formé de calcaires du Malm dont l'épaisseur varie entre zéro (extrémité est) et 320 mètres (au sud-est). L'aquifère est délimité dans sa partie inférieure par les marnes oxfordiennes épaisses de 80 mètres. Les calcaires sous-jacents (Dogger) sont considérés comme indépendants du point de vue hydraulique. La topographie de la surface des marnes oxfordiennes met en évidence la présence de la terminaison périclinale d'un large anticlinal au centre du plateau de Bure alors qu'un large synclinal se développe au sud. Les calcaires du Malm renferment trois horizons marneux. Les essais de traçage ont cependant montré que ces horizons ne représentent pas des aquicludes régionaux. Les essais ont aussi permis une subdivision assez détaillée des sous-bassins versants alimentant les sources en périphérie du plateau de Bure. Sur la base de ces essais et des mesures de niveaux d'eau dans les forages une limite a été dessinée, séparant les eaux s'écoulant vers le sud (zone Porrentruy – Bure – Croix) de celles s'écoulant vers le nord. Les estimations des niveaux noyés comparés au niveau du toit des marnes oxfordiennes permettent de délimiter, au centre du territoire, une zone dans laquelle les écoulements sont libres dans les conduits karstiques («Shallow karst»). L'épaisseur de la zone noyée augmente au nord et surtout sud où elle atteint son épaisseur maximale avec environ 300 mètres. L'épaisseur de la zone non-saturée présente d'importantes variations, elle est maximale au centre du terrain (environ 200 mètres).

Les calculs du modèle numérique reproduisent globalement les observations de charges hydrauliques et de débits des sources. Ils confirment les hypothèses faites sur les parametres hydrauliques et suggèrent l'existence d'un réseau karstique bien développé sur l'ensemble du secteur.

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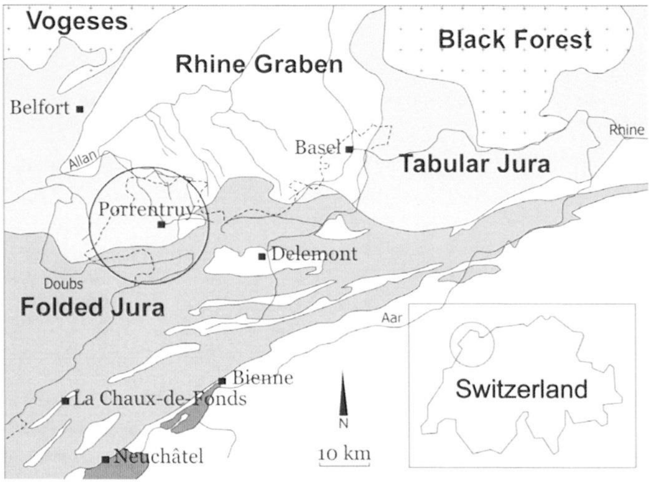

Fig. 1. Regional geographical and geological settings of the study area. Circle indicates the Bure plateau. Solid lines indicate rivers; dashed line marks the Swiss-French boundary.

1. Introduction and aims

The Bure plateau is a sparsely populated area, underlain by a karst aquifer. As it is relatively pristine, conclusions drawn from field observations refer to the general natural behavior of such karst hydrogeological systems. For that reason it has been the target of several hydrogeological studies since the early nineties (Grasso & Jeannin 1994, Jeannin 1995a, b, Jeannin & Grasso 1995a, b, Jeannin & Maréchal 1995). These studies have included discharge measurements and hydrograph analyses, tracing experiments and water balance calculations, hydrochemical measurements and surface geophysical experiments mainly focused on the Milandrine cave system, which is the largest explored karst system in the area.

So far, the only overview of the Bure plateau hydrogeology has been made by Gretillat (1998). However this work was based on a limited data subset.

A large number of experiments and observations have been carried out for academic research (Karst Research group at CHYN, University of Neuchatel), as well as for the construction of the A16-Transjura highway, which will cross the Bure plateau.

The aim of the present paper is to summarize and analyze available geological and hydrogeological information in the area, in order to provide a better understanding of the regional hydrogeology.

In order to synthesize the existing data in a semi-quantitative way, a distributive hydrogeological model was constructed. Construction of the conceptual and mathematical models required a precise reconsideration of the geological settings, the aquifer geometry and our general notion of the hydraulic functioning of the area.

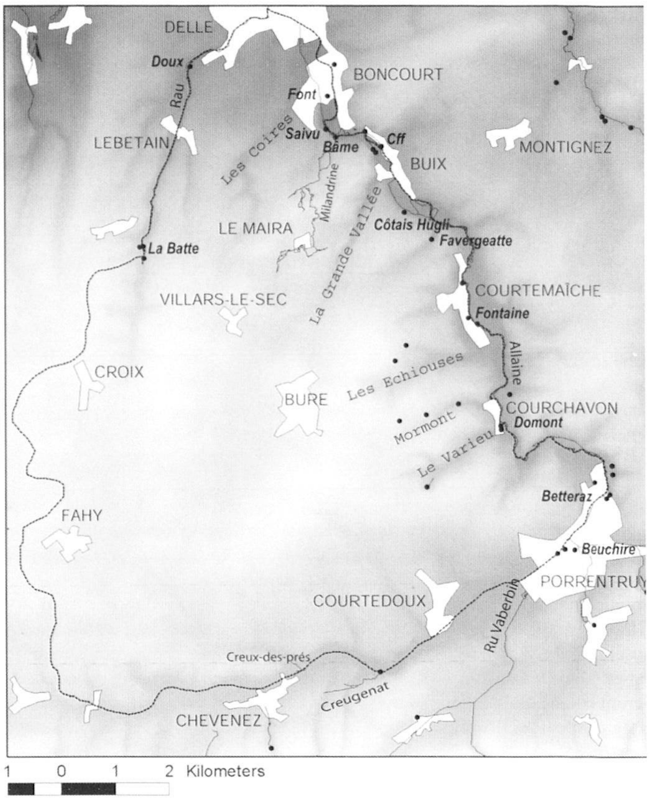

Fig. 2. Research site topography. The Bure plateau is bordered (dashed line) by the Allaine river to the East and by the Porrentruy – Chevenez – Grandfontaine dry valley to the South. The Delle – Lebétain valley forms the western border of the plateau. In the vicinity of Fahy the delineation follows the topographic high. The Bure plateau is dissected by five NE-SW oriented dry valleys (*Le Varieu, Mormont, Les Echiouses, La Grande Vallée*, and *Les Coires*). Thin solid lines indicate explored cave systems, spring locations are marked by black dots.

2. General context

2.1. Geographical situation and hydrography

The *Bure plateau* is located along the Swiss-French border in *Ajoie, canton Jura*, NW Switzerland at the southern margin of the *Plateau Jura*, to the west of the southern end of the *Rhine Graben* (Fig. 1).

The Bure plateau is drained by the *River Allaine* (Fig. 2), which is a tributary of the *River Doubs*. The average discharge of the Allaine river is about 3 m^3/s. Minimum discharge measured in the eighties was 370 l/s, while the maximum discharge estimated during the flood of 1983 reached 90 m^3/s. The gradient of the riverbed is about 5 m/km.

The plateau is bordered by the Allaine river to the West and by the *Porrentruy – Chevenez – Grandfontaine dry valley* to the South (Fig. 2). This valley is often flooded after high precipitation events. A partly explored underground river, the *Ajoulotte* stream, underlies the valley bottom. Several springs

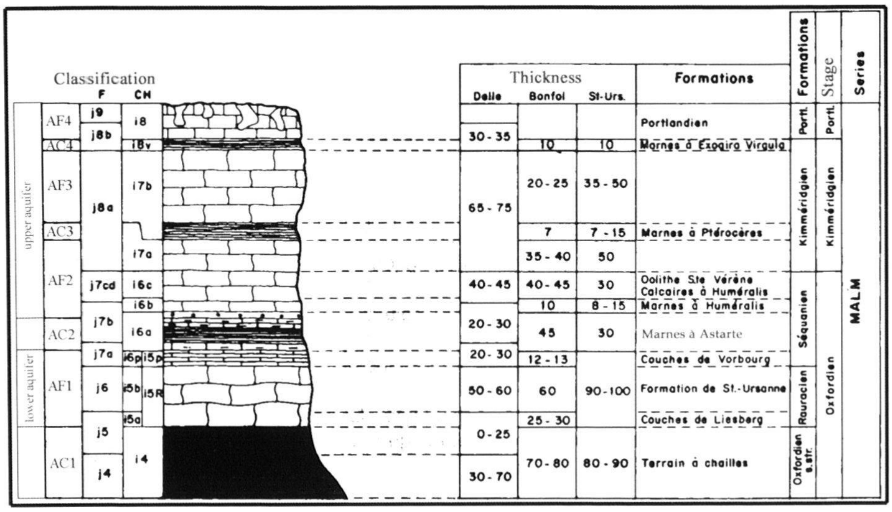

Fig. 3. Research site lithostratigraphy and hydrostratigraphy (After Gretillat 1996). The Swiss (CH) stratigraphic codes are used in this paper. French (F) codes are shown for comparison. The thicknesses of different formations are shown for three different locations.

are located along the *Delle – Lebétain valley*, delineating a hydrogeological boundary to the North-West of the Plateau. In the vicinity of *Fahy* the hydrological delimitation is uncertain, it is assumed to follow the topographic high.

The area of the Bure plateau, delineated as described, is 83 km^2. The highest topographic elevation is about 630 m above see level and the lowest point is 360 m above see level. The highest difference in elevation between the plateau and the Allaine outflow is about 270 m. Excepting some valley incisions the topography of the plateau is rather smooth with a relief in the range of 60 m to 150 m. Between Porrentruy and Delle the plateau is dissected by five dry valleys (Fig. 2). These are *Le Varieu, Mormont, Les Echiouses, La Grande Vallée* and *Les Coires – Goulattes*. The largest of these valleys is "*La grande valle*".

From the Bâme spring upstream to the South a large karst system has been explored by speleologists. It extends directly from one end to the other over 3 km, between *Boncourt* and le *Maira*. Its total length is about 10 km. It contains an underground river called "*Milandrine*". In the South, the *Creugenat* and *Creux-des-Prés* systems have been explored over nearly two kilometers along the Porrentruy – Chevenez – Grandfontaine dry valley. Some other small caves (up to 30 m long) are known in the area of Rocourt, Porrentruy, Courchavon and Courtemaiche.

Surface morphology of the Bure Plateau is characterized by various types of karstic landforms (dolines, dry valleys and shafts). There are no significant surface streams over the site.

63% of the plateau is covered by pasture, 34% is covered by forests, the rest (3%) is used for tillage.

2.2. Geological settings and lithostratigraphy

The Bure plateau is underlain by slightly folded layers of Triassic to Late Jurassic shallow marine limestones and marls. The total thickness of this mesozoic block is 1000 – 1500 m (Labhart & Decrouez 1997).

The Malm limestones form the main aquifer. Older formations are not of interest in this study. The total thickness of the Malm is about 300-400 m. These limestones are underlain by the Oxfordian Marls, which have a thickness of up to 100 meters (Fig. 3).

The *Oxfordian Marls Formation* (i_4) is subdivided into two different sedimentary units (Laubscher, 1963, Liniger 1970). In the lower part pyritous clay with pyritized ammonites (*Renggeri Marls*) occures. Overlying sediments are called "*Terrain à Chailles*", which reflects the presence of siliceous nodules. The upper part of the formation consists of marls or sandy marls, which alternate with beds bearing flints, corals or crinoids.

Rauracian reef limestones (i_{5r}) have a beige to gray color and are rich in corals. The thickness of these sediments can vary between 60–76 m. This unit is divided into two formations. The lowermost is called *Couches de Liesberg* (i_{5a}), and consists of dark-gray limestone banks alternating with lime and marly limestone at the bottom. These sediments often contain *Millericrinus* remnants and corals. The uppermost beds consist of coarse oolitic limestones in the north and fine grained limestones in the south. The overlying *St-Ursanne Formation* (i_{5b}) consist of pure, white chalky limestones containing coral reefs (patch-reefs) or coarse breccia layers. In the south, pelletal limestones indicate the proximity of a reef ridge facies.

The Milandrine cave itself is located within layers of Rauracian limestone. These limestones are directly underlain by the Oxfordian Marls.

The *Couches de Vorbourg* (i_{6p}) occur at the base of the Sequanian unit. These thick bedded light color and compact limestones often show a limnic influence with quartz grains and limestone breccias (*Cailloux Noirs*). They are usually morphologically well exposed.

Astarte Marls (also called *Natica Beds*) (i_{6a}) are the lowermost and thickest (30–40 m) of the three Malm marl layers in this area. Astarte Marls display a gradual transition from the underlying Rauracian limestones. Marl layers alternate with

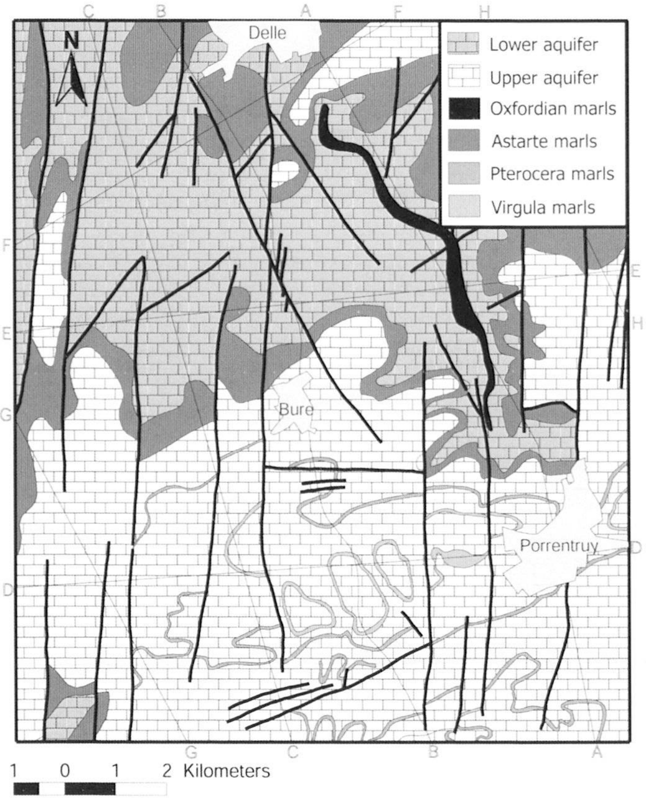

Fig. 4. Hydrostratigraphic map. Tertiary and Quaternary sediments are omitted. Marl levels are indicated for orientation. Malm limestones are merged for simplicity. Thick lines mark tectonic features; cross sections are indicated by thin solid lines.

fine grained, gray, often oolitic or crinoidal limestones with Astarte coquinas, reef limestones or sandstone layers. The upper part of this formation is typically pure crinoidal marl.

Humeralis Marls (i_{6b}) are yellow chalky-marls, which contain coquinoid layers and echinoderm breccia. Fe-ooid bearing layers are also common, and rich of fossils. The *St-Vérène Oolite* (i_{6c}) consist of oolith bearing sediments whereas the concentric structure of the oolith grains is not visible.

Lower-Kimmeridgian limestones (i_{7a}) are light, well stratified, with intercalations of fine breccia and pseudoolitic layers. They have a thickness of 35–50 m.

The *Pteroceras Marls* (i_{7b}) are 10 m thick, limy and sandy marls bearing bivalves and *Pteroceras.*

The Upper-Kimmeridgian limestones (i_{7b}) are well stratified, sometimes even thin layered, light colored sediments which often contain marl intercalations. They have a thickness of 30–50 m. More than 500 dinosaurs tracks have been found in this formation in the vicitnity of *Courtedoux*.

Virgula Marls (i_{8v}) show a sharp transition from the underlying limestones. These marls have bluish-gray or dark brown color, bearing the masses of *Exogyra Virgula*. The top of this unit contains the intercalations of laminated crinoid limestones, or greenish glauconitic limy marls. Their thickness is approximately 10 m.

Portlandian limestones (i_8) are similar to the Kimmeridgian sediments, but generally contain more fossils. These limestones are sometimes white, fine bedded, chalk-like fine grained sediments with a maximal thickness of 20 m in this area.

Tertiary sediments are very rare in the area. Some small sandy gravel bodies are situated over the Bure plateau in the area of Porrentruy and Courchavon. The thickness of these sediments does not exceed a few meters.

Quaternary loess sediments cover about the 30% of the Mesozoic rocks in the area. Quaternary alluvial sediments are present along the Allaine river, and along the Rocourt-Porrentruy valley. The thickness of the alluvium is about 10–20 meters. These alluvial bodies form separate aquifers, which have hydraulic connection either to the river or to the Malm aquifer at many locations.

The Malm plateau is dissected by NS (0°–180°), NW-SE (150°–330°) and NE-SW (60°–240°) oriented faults (Kiraly et al. 1971), resulting in a succession of long horst and graben structures. The first system is related to the formation of the Rhine Graben, while the others are realated to the Jura folding.

2.3. Hydrogeological setting

Bure Plateau Aquifer consists 300–400 m of Malm limestones. The aquifer is underlain by the Oxfordian Marls (100 m thick). Deeper underlying sediments of Dogger age can be considered to be hydraulically independent (Gretillat 1998). These two aquifers can only communicate in strongly tectonised zones, such as at the contact of the tabular and folded Jura (south of research area).

The Malm aquifer contains three low-permeability marl intercalations (Fig. 3). The lowermost is the 40m thick Sequanian Astarte Marls Formation. Due to gradual change from the Rauracian sediments to Sequanian marls, and also because of large normal faults with displacements of 30 to 40 meters, the Astarte Marls can not be considered as aquiclude at the scale of the Bure plateau. As shown in the following sections tracing experiments confirm this assumption.

The two succeeding Kimmeridgian marl layers, with a thickness of about 10 m each, play a very restricted role in the regional flow patterns.

Jeannin & Grasso (1995a) calculated the effective infiltration taking place over the upstream catchment of the Milandrine river (*Milandrine amont*) for the early nineties. According to their calculations based on potential evapotranspiration, about 50% of the average yearly precipitation (1000 mm) is effective infiltration (500 mm/y). From this quantity nearly 50% has to be considered as quick flow, feeding directly to karst conduits. The rest is retarded as storage in the epikarst and in the main aquifer. This is in agreement with the estimations of Kiraly (1998) who pointed out that this division is a result of

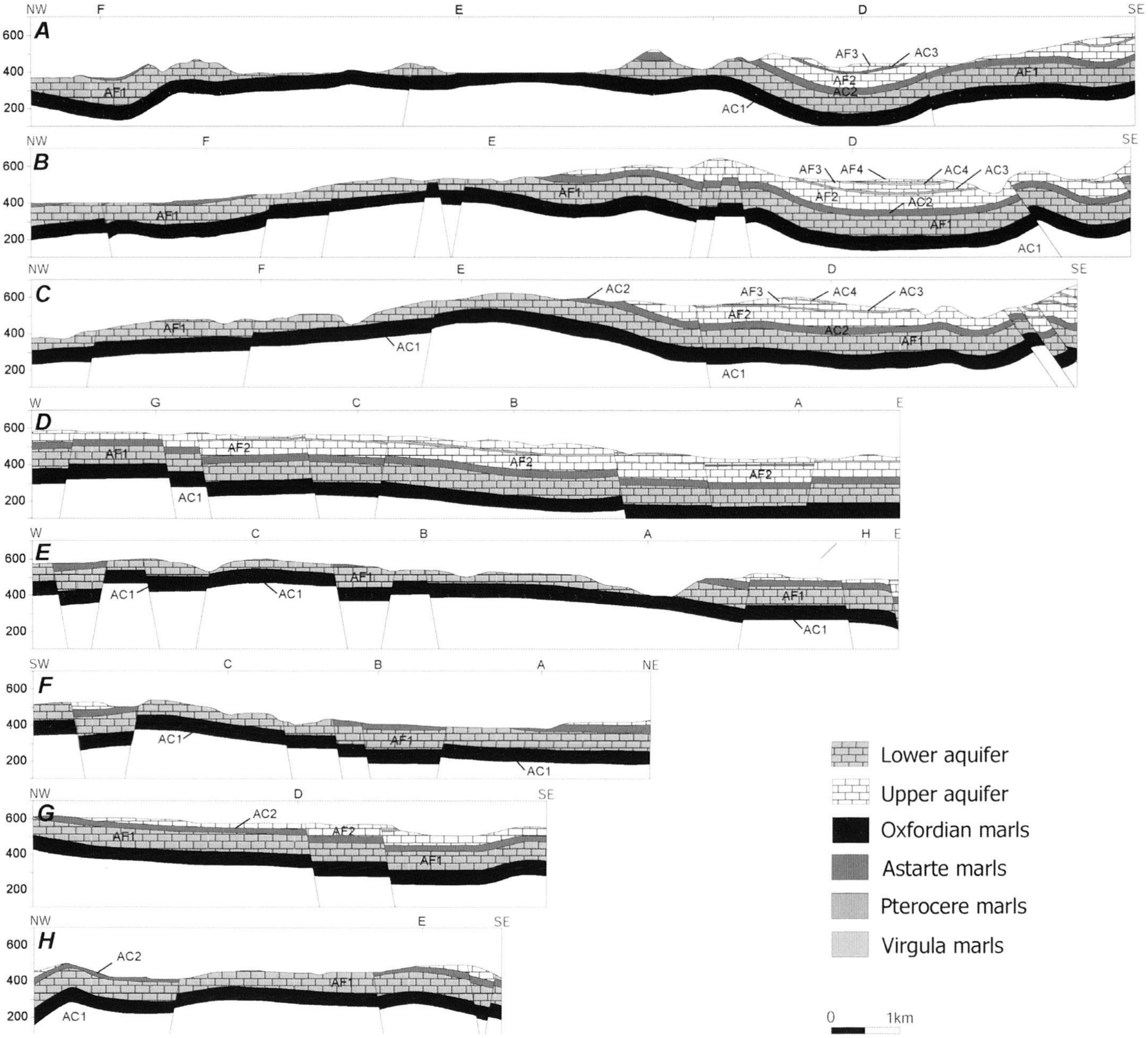

Fig. 5. Hydrostratigraphic cross sections. Hydrostartigraphic units are labeled with their codes for orientation. Vertical exaggeration is 2.5.

the water-capturing effect in the epikarst zone. Gretillat (1998) also made calculations on the effective recharge for the late eighties, and came to very similar conclusions (48% effective infiltration of precipitation of 1013 mm/y).

Tracing experiments have shown that several karstic drainage basins are present on the Bure Plateau (Gretillat 1998), each having its own discharge point (karst spring).

The largest system ($Q_{average}$ = 800 l/s) discharges at the Beuchire spring. Its catchment covers one-third (37 km^2) of the Bure Plateau, and also extends to the south of the Porrentruy-Chevenez-Grandfontaine dry valley. Some sections of the karst conduit network have been explored by cavers, such as the Creugenat and the Creux-des-Prés caves. The Creugenat is a karst window at low flow conditions (large collapsed doline in contact with the water table at its bottom). At very high water stages, the doline floods and becomes a spring having a discharge of several cubic meters per second. One conduit can be dived upstream from the doline and leads to about 2 km of cave passage. It ends in further siphons. A significant discharge flows through the conduit.

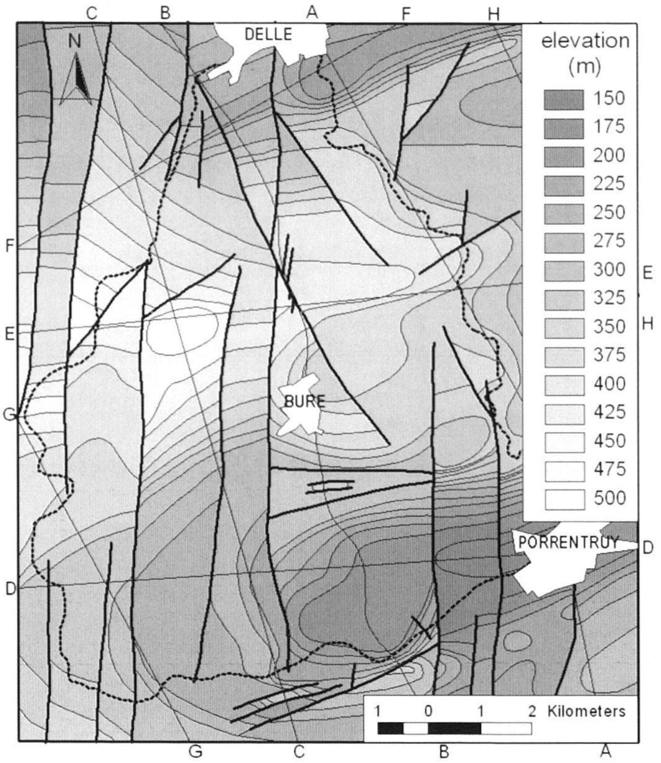

Fig. 6. Structural surface of the Oxfordian Marls. Dashed line marks aquifer boundaries. Thick lines indicate tectonic features. Cross sections are marked by thin solid lines.

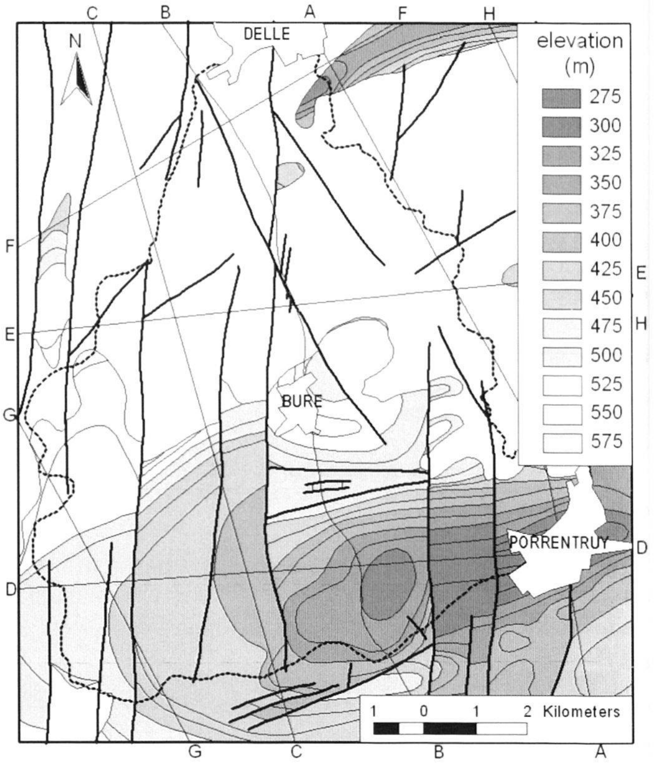

Fig. 7. Structural surface of the Astarte Marls. Thick solid lines indicate faults. The aquifer boundary is marked by dashed line; thin solid lines indicate cross sections.

The Creux-des-Prés opens as a vertical shaft of about 20 meters reaching an underground stream at its bottom. The stream can be followed downstream for about 50 meters and upstream for about 300 meters. Siphons at both ends should be dived to further explore the cave.

The Milandrine catchment is the second largest in the region covering an area of 13 km^2. The combined average discharge of the Saivu, Bame and Font springs is in the range of 200 l/s. It encloses the Milandre cave which stretches over a total length of more than 10 km. The underground river of this catchment can be followed for some 4.6 km from the Bâme spring upstream. Flow is mainly free surface flow. Only the downstream part (500 m) is phreatic. River discharge ranges between 20 l/s – 1500 l/s.

The other smaller systems remain completely unexplored. They are related to the following springs: Côtais Hugli, Favergeatte, Fontaine, Domont, Trou de la Doux, La Batte (Fig. 2).

3. Hydrogeological data and interpretation

With the exception of the synoptic work of Gretillat (1998), the only articles published focus on particular phenomena or methodology. These articles worked on data and observations concerning mainly the Milandrine cave system, its catchment area and its springs. In the following sections we attempt to summarize geological and hydrogeological data from the whole plateau into an integral conceptual model.

3.1. Aquifer geometry

An understanding of the three dimensional aquifer geometry is essential for the comprehension of the hydraulic functioning of the aquifer, and also for constructing a coherent distributive numerical groundwater flow model.

Based on the existing geological interpretations (Atlas Géologique de la Suisse 1963, Carte Géologique de la France 1985) and recent borehole data obtained from the construction works of the Transjura Highway (MFR 1993, 1996), a hydrostratigraphic map of the region at 1:25000 scale has been established. A reduced version of this map is shown on Fig. 4. This interpretation also includes a set of geological cross sections (Fig. 5) and structural maps of the Oxfordian and Astarte Marl surfaces (Fig. 6, 7) which provide an understanding of the geological structure in three dimensions.

Structural surfaces clearly show the presence of a wide WNW-ESE oriented syncline, which is marked out by the Porrentry-Chevenez valley. The periclinal termination of a wide anticline, parallel to the syncline, is present in the region of Bure, which corresponds to the Bure plateau. These structures are dissected by NS (0°–180°), NW-SE (150°–330°) and NE-SW (60°–240°) oriented faults (Kiraly et al. 1971). The first system is related to the formation of the Rhine Graben, while others are a consequence of the tectonic activity during the Jura folding.

Since the Oxfordian Marls form a persistent hydraulic threshold, the thickness of the Malm calcareous aquifer is the difference between the aquifer surface topography and the top of the Oxfordian Marls. While the aquifer thickness exceeds 300 m to the north-west of Porrentruy, it decreases to some meters in thickness along the Allaine River in the area of Buix (Fig. 8). Here the Oxfordian Marls are covered only by Quaternary alluvial sediments.

The Astarte Marls are dissected by surface topography in the region of Bure and, because of the dry valleys mentioned above, they have a sinuous surface appearance in the area of Courchavon. To the north of Bure, no Sequanian or Kimmeridgian Limestones occur over the plateau, except for a small body located to the SW of Boncourt.

3.2. Hydraulic parameters

Some borehole tests were made in the Malm aquifer both in the Maira region, and further to the east in the area of Delemont.

The hydraulic conductivity of the Rauracian limestones, measured from borehole tests, is in the range of $10^{-6} - 10^{-7}$ m/s (Fleury & Allemann 1991, Jeannin 1995b). Both lower and higher values were measured, but the mentioned values are typical. The hydraulic conductivities of Sequanian and Kimmeridgian limestones are similar (Fleury & Allemann 1991).

As the displacement along faults (20–40 m) is generally more than the thickness of Kimmeridgian marls, and as these formations are relatively thin, they can probably be neglected as hydraulically continuous thresholds. Tracing tests confirm this assumption (see next section).

The hydraulic role of the Sequanian marls (Astarte Marls) is not evident. Tectonic displacement exceeds their thickness in some cases, but it is usually smaller. One of the aims of this study is to estimate whether this layer can be considered as a hydrogeological barrier or not. As we see in the following section, though marly sediments are usually of a low hydraulic conductivity, they do not strongly influence the flow field, probably because of karstification phenomena.

The estimation of the conductivity of fractured zones is very approximate, as there is a large variation of values even over the same formation (Jeannin 1995a). We assume that the conductivity values along fractured zones are one order of magnitude higher that the matrix conductivity. Numerical modeling performed by Kovacs et al. (2002a) appears to support this assumption.

Fleury & Allemann (1991) provides measured values for the storativity of confined Malm limestones in the area of Delémont. These values vary between $6 \cdot 10^{-5}$ and $3 \cdot 10^{-4}$ [–] in the 255 m thick confined aquifer. Jeannin & Grasso (1995b) estimated the effective porosity of the Bure aquifer to be in the range of 0.7 – 1 %.

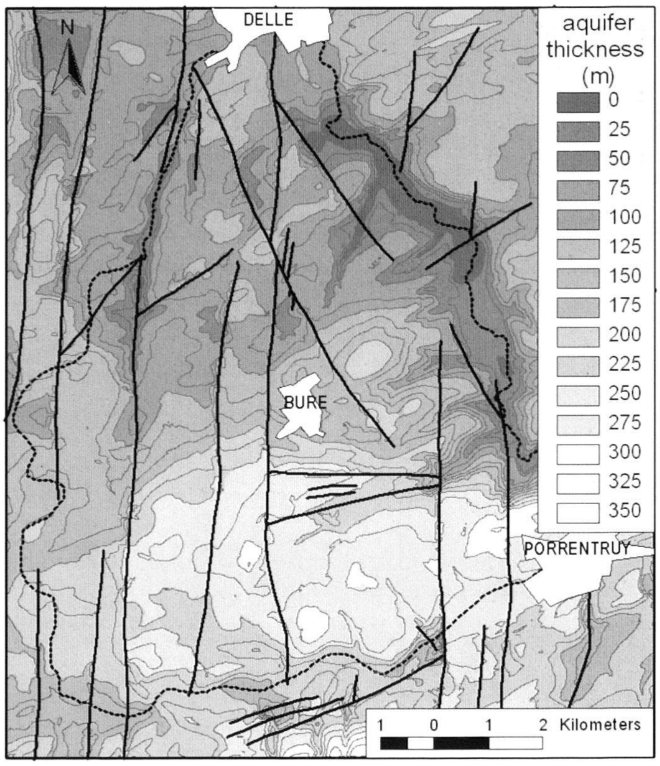

Fig. 8. Aquifer thickness map; obtained as the difference between surface topography of the Mesozoic rocks and of the Oxfordian Marls. In the area of Buix, along the Allaine river Oxfordian Marls are covered exclusively by Quaternary alluvial sediments.

3.3. Aquifer definition and catchment areas delineation

Several tracing experiments (Fig. 9) have been carried out in the region since 1970 (Fleury 1984, Gretillat 1998, Favre 2001). The most frequently used tracers were fluorescent solutes (uranine, amidorhodamine, sulforhodamine and napthionate) and bacteriophages. Measured average velocities range between 1 and 700 m/h, but are usually in the range of 20–50 m/h.

The Bure plateau is hydraulically bordered by the Allaine river to the West and by the *Porrentruy – Chevenez – Grandfontaine dry valley* to the South. The southern border contains an underground river, the *Ajoulotte stream*, that underlies the valley bottom. These valleys act as the base levels of the plateau. Several springs are located along the *Delle – Lebétain valley*, delineating a hydrogeological boundary to the North-West of the Plateau. In the vicinity of *Fahy* the hydrological delimitation is uncertain, information obtained from tracing tests are very sporadic, and hydraulic boundary is assumed to follow the topographic high.

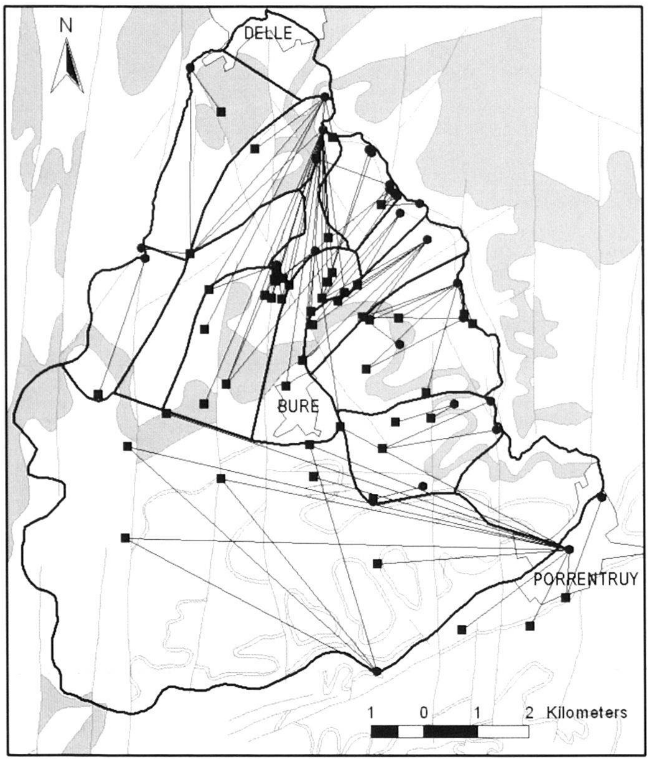

Fig. 9. Delineation of water catchments based on tracing tests and water balance calculations. (Modified after Gretillat 1996, Grasso & Jeannin 1994, and Favre 2001). Figure shows a selected set of dye tracer pathways, which link tracer injection points (quadrangles) and monitoring points (dots). Minor catchments at the northern and eastern extremities of the domain were determined by numerical models.

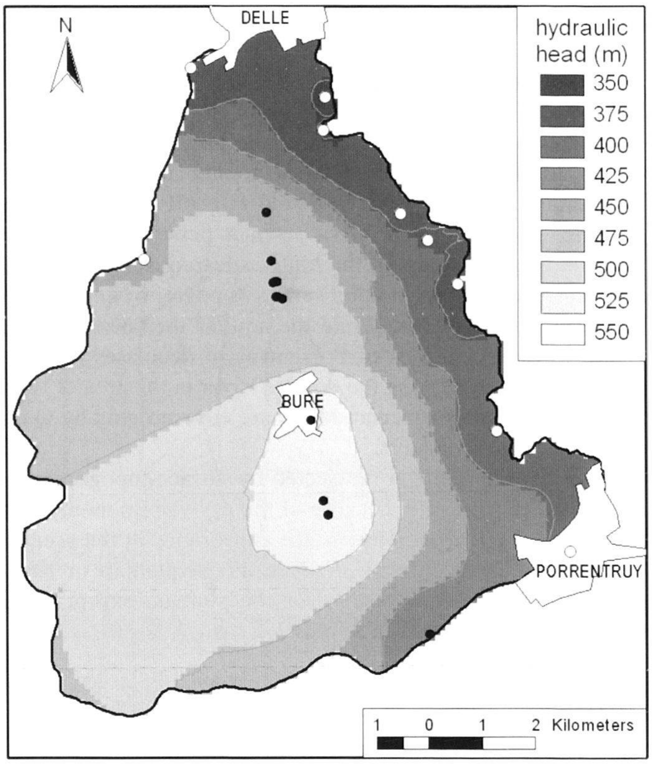

Fig. 10. Water table map. It was obtained by Inverse Distance Weighted Interpolation between piezometric levels (black dots) and spring topographic elevations (white dots). Because of the sparse available piezometric data, this map provides only a loose approximation of the mean hydraulic heads throughout the low-permeability fissured matrix.

Tracing experiments all confirmed the above mentioned delimitation, since no tracers passed these hydraulic boundaries.

Detection of artificial dyes in karst springs facilitated the delineation of several water catchments (Gretillat 1998, Grasso & Jeannin 1994, Favre 2001). Water budget calculations were also taken into account when delimiting water catchments. Based on these studies and numerical modeling experience (Kovacs et al. 2000a, b), a detailed delineation of catchment areas is shown on Fig. 9.

While the largest catchment area belongs to the Beuchire spring, tracing experiments supplied the most detailed information over the Milandrine catchment, where a greater number of experiments took place. Speleological exploration made the localization of tributaries confluences possible, and facilitated the measurement of their respective discharge rates.

Tracing experiments have another important consequence, which fundamentally influences our conception about the hydraulic functioning of the Malm aquifer: They clearly show that some tracers injected in certain zones into the aquifer above the Astarte Marls reappear in springs below the Astarte Marls. That means that Kimmeridgian Astarte Marls – according to our assumption based on structural properties – do not interrupt the aquifer hydraulic continuity in these zones. However the role of the Astarte Marls is not obvious at catchment scale, as there is no evidence whether infiltration waters penetrate the Astarte Marls all over the aquifer or not.

The zone where tracers could penetrate the Astarte Marls coincides with the zone where marls are located within the unsaturated zone and the hydraulic gradient is vertical. This zone also corresponds to the upstream part of the Milandrine catchment. Consequently any tracers injected south of this zone flow to the south and reappear in the Beuchire spring. However, there is no sufficient information to determine whether groundwater flows on the top, or below the Astarte Marls.

By way of the most obvious approach, all of the Malm sediments superposed on the Oxfordian Marls are considered as an integral unit in this study.

3.4. Piezometric surface

Although water table in karst aquifers can be only poorly approximated by a few measurements obtained from piezome-

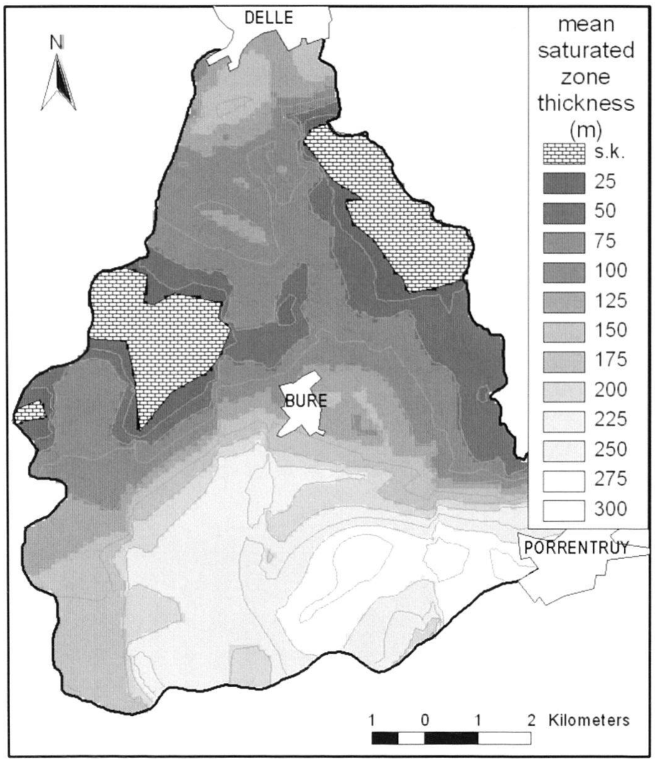

Fig. 11. Mean saturated zone thickness map. It was calculated as the difference between interpolated water table and the top of the Oxfordian Marls, consequently it is very approximate. In the area of Boncourt – Buix and St-Dizier the thickness of the saturated zone decreases dramatically, indicating shallow karst conditions (s.k.).

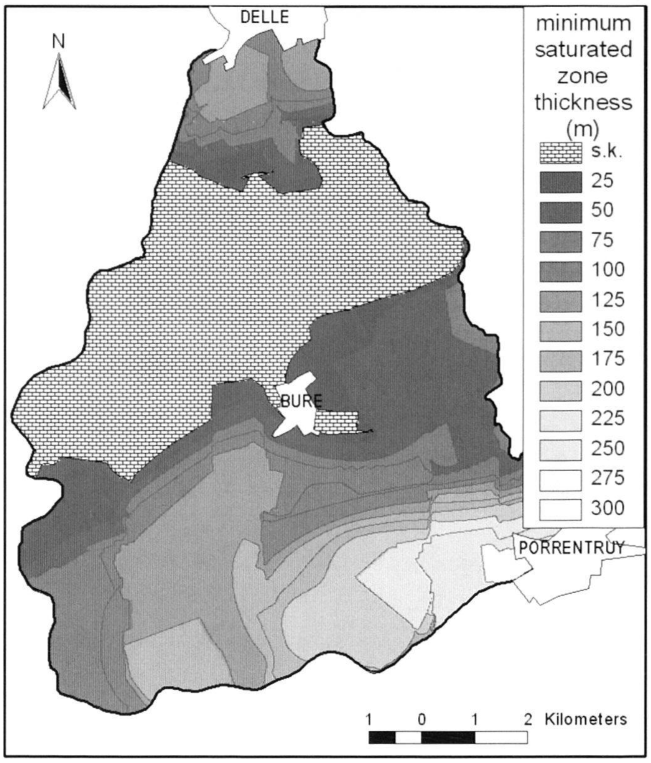

Fig. 12. Minimum saturated zone thickness map. This map demonstrates a minimum estimate of the thickness of the saturated zone, assuming zero hydraulic gradient upstream of the springs. The saturated zone thickness throughout the northern part of the research site was calculated as the difference between the topographic elevation of the Saivu spring and the surface topography of the Oxfordian Marls. The saturated thickness over the southern part of the site was calculated as the difference between the topographic elevation of the Beuchire spring and the surface topography of the Oxfordian Marls.

ters or boreholes (Jeannin 1995a), these data can be used for roughly estimating regional head distribution and hydraulic gradients. A water table map has been established based on piezometric data obtained from a selected set of piezometers, and spring elevations. In the course of data selection, boreholes intruding deep into the saturated zone were considered exclusively, and shallow penetration piezometric data were rejected, as they can be false and misleading.

The result of the Inverse Distance Weighted interpolation is presented in Fig. 10. Since no piezometric observations are available in the western part (Fahy – Croix) of the domain, this map has to be considered as a very approximate one.

A piezometric dome extends to the south of Bure (Haut du Mont) with a maximum piezometric head at 580 m a.s.l. Confirmed by tracer flow directions, this dome designates a NW-SE oriented regional groundwater divide along the line connecting Porrentruy, Bure and Croix. To the north of this line, the general flow direction is NE. In the Southern regions the general flow direction is ESE.

The thickness of the saturated zone was calculated as the difference between the interpolated piezometric surface and the Oxfordian Marls surface (Fig. 11). Saturated zone thickness reaches 300 m in the southern part of the site; it drops down to zero in the area of Boncourt – Buix and St-Dizier, indicating shallow karst conditions.

The maps presented here are based on incomplete and very approximate data. In fact piezometric levels measured in boreholes at low water conditions are always higher than the hydraulic heads in the karst conduit network. Piezometric data indicate the mean water levels in the fissured matrix. Consequently this approach maximizes the thickness of the saturated zone at low water levels.

3.5. Regional hydrogeological conceptual model

Field observations and measurements interpreted above from a regional perspective are now merged into a general conceptual model.

The Bure aquifer consists of karstified limestones varying in thickness between 0 and 320 meters. Malm sediments con-

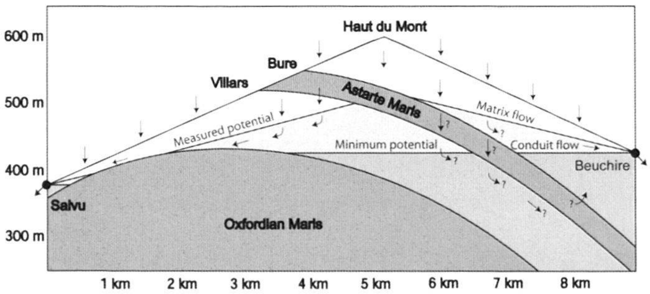

Fig. 13. Conceptual model of the Bure aquifer. This N-S oriented theoretical cross section between Boncourt and Courtedoux shows the minimum estimate of the hydraulic heads in the karst conduits (assuming zero hydraulic gradient) and the mean water table (obtained from piezometers). Arrows indicate flow directions.

tain marly intercalations, which seem to be sufficiently karstified to allow groundwater flow. Thus the entire Malm sequence (above the Oxfordian Marls) is considered as a single heterogeneous aquifer.

Because of folding and subsequent erosion, the aquifer considerably thins over the anticline, while at the southern part of the aquifer it remains substantially thick.

The saturated zone also shows a large variation in thickness. According to available piezometric data over the anticline, the thickness of the saturated zone is negligible (Fig. 11). In this shallow karst zone, mainly unsaturated and channel flow takes place and the hydraulic gradient is determined by the topography of the Oxfordian Marls.

When assuming a zero hydraulic gradient upstream from the springs, we make a minimum estimate of the piezometric level in the karst conduits. This approach has been applied to the two main springs (Saivu and Beuchire) in the region (Fig. 12). While the former better characterises the low-water saturated thickness over the northern part of the domain, the latter relates to the southern part of the aquifer.

As piezometric data refer to the hydraulic heads in the fissured matrix and conduit flow also possesses some hydraulic gradient, which was not considered during the minimum piezometric level calculations, Fig. 11 shows thicker saturated zones than Fig. 12.

Development of observed and minimum water tables is shown in Fig. 13. Real hydraulic heads over the conduit network occur between these two surfaces. At high precipitation events conduit hydraulic heads can exceed average observed (matrix) piezometric levels.

Infiltration waters, after having been stored or distributed by the epikarst zone, descend through the unsaturated zone down to the saturated zone. Water from the fissured matrix flows through the conduit network towards the karst springs. The thickness of the unsaturated zone varies greatly; while it exceeds 150 meters in certain regions, in other parts of the aquifer it reaches only a few meters (Fig. 14).

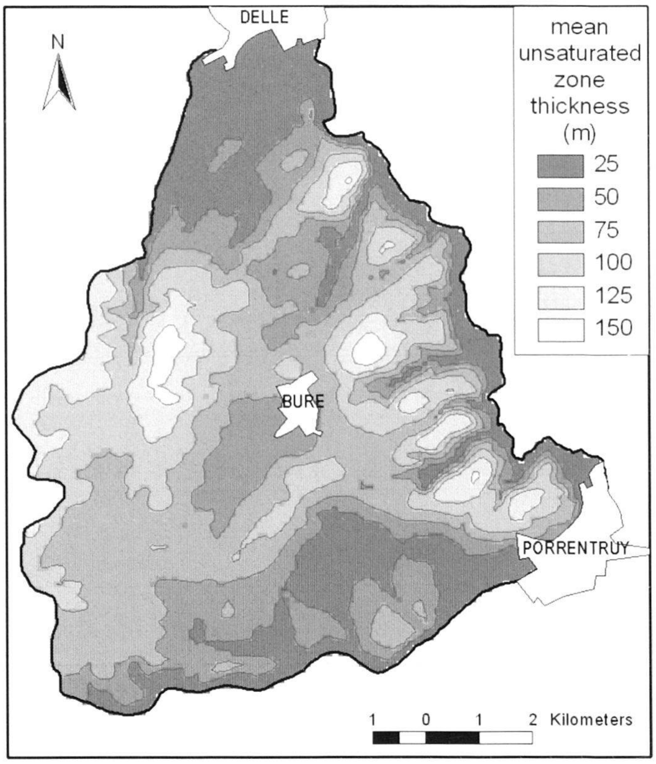

Fig. 14. Mean unsaturated zone thickness. It was calculated as the difference between the surface topography and the mean water table.

4. Numerical model

The aim of numerical modeling was to synthesize data, observations and conceptions presented above into a coherent quantitative model. Numerical model allowed for the verification of conceptions on the structure and hydraulic behavior of the aquifer.

As noted in previous sections, marl layers do not interrupt the hydraulic continuity of the Malm aquifer on a regional scale. Consequently the entire Malm aquifer (above the Oxfordian Marls) can be considered as a single heterogeneous one, and the model geometry can be simplified to a two-dimensional mesh of finite elements (vertical heterogeneity is neglected) (Fig. 15).

As a first approximation steady-state and confined flow was simulated. Darcian flow was supposed in the entire aquifer, in spite of the fact that turbulent flow takes place in several karst conduits.

The entire aquifer is considered to be homogeneous, and an averages of the measured hydraulic parameters (see § 3.2.) as uniform values were applied to the fissured rock matrix throughout the model domain. Transmissivity values were set proportional to the thickness of the saturated zone over each finite element. Initial hydraulic conductivities of the conduit system are estimated values, which were later modified during

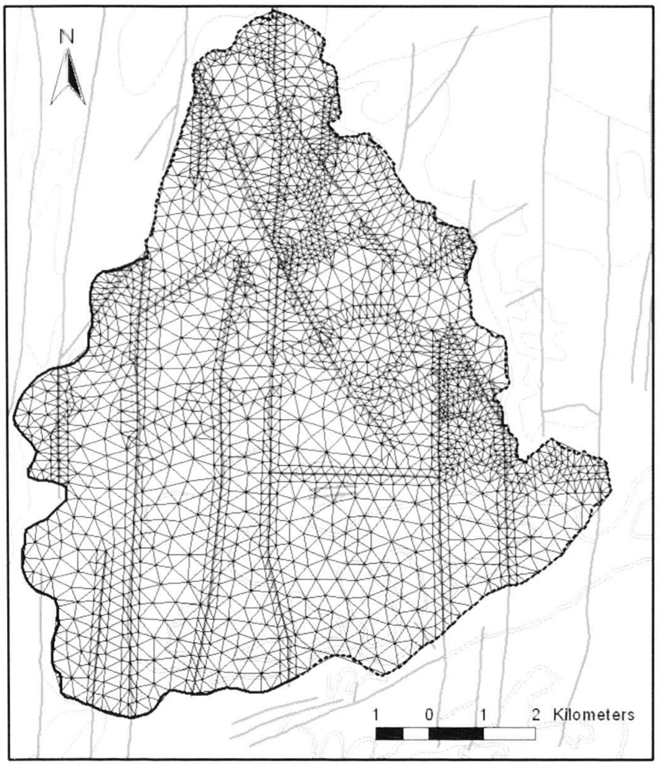

Fig. 15. Finite element mesh and boundary conditions. Solid line designates Neumann no-flow type boundary conditions; dashed line marks Dirichlet boundary conditions. The average size of linear triangular elements is about 300 m. Dirichlet boundary conditions were obtained by linear interpolation between principal spring elevations.

the calibration process. Observed hydraulic head distribution, average spring discharges and drainage basin boundaries were taken into account during calibration. A uniform effective infiltration of 500 mm/y (Jeannin & Grasso 1995a) was imposed throughout the whole model domain.

4.1. Modeling tools

GIS tools ArcView and ArcInfo (ESRI) were used for data transfer between observations, the conceptual model and the mathematical model. These tools were also used for data exploitation, and for the construction of the superelement mesh. Finite element mesh was generated by the T-mesh function of the FEFLOW (WASY) groundwater modeling code.

The combined discrete channel and continuum approach (Kiraly & Morel 1976, Kiraly 1985, 1988) was applied to simulate groundwater flow. This approach allows a combination of 1-D, 2-D and 3-D linear or quadratic finite elements to be used. Using the code FEN1 saturated, steady-state groundwater flow in two or three dimensions can be calculated. The formulation of the finite elements is based on the Galerkin weighted residual approach. The resulting system of linear equations is solved by the frontal elimination technique.

Tab. 1. Measured and calculated mean spring discharges. The Beuchire and Doux catchments (*) extend beyond the model domain, consequently simulated discharges of these springs are less than the measured values.

SPRING	**MEASURED DISCHARGE (M3/S)**	**CALCULATED DISCHARGE (M3/S)**
SAIVU	0.155	0.205
COTAIS-HUGLI	0.010	0.019
FAVERGEATTE	0.030	0.025
FONTAINE	0.065	0.077
DOMONT	0.040	0.060
BEUCHIRE*	0.800	0.600
BATTE	0.020	0.053
DOUX*	0.150	0.060
FONT	0.050	0.050

4.2. Model results and discussion

During the calibration process several model scenarios were tested. As a first scenario, measured hydraulic parameters (K_m = 7.0E–7 m/s) and observed conduit network was incorporated in the model. This model yielded extremely enhanced hydraulic heads, and feeble spring discharges.

Subsequently simulated head distribution was adjusted by increasing the hydraulic conductivity of the fissured matrix (K_m = 1.5E–5 m/s), while the conduit system was not extended. By this approach observed head distribution could be simulated, but calculated spring discharges still remained extremely low (except the one of the imposed conduit system) (Kovacs et al. 2002a).

Finally, conduit networks were implemented into each catchment. They have been extended to the catchment boundaries in order to adjust simulated head distribution. Manually constructed synthetic conduit networks follow a hierarchical pattern, converging on observed karst springs. Initial conduit hydraulic conductivity was estimated to be 8 m^3/s from mean discharges and hydraulic gradients in the conduit network. Conduit network density was increased until excessive heads disappeared. Steep gradients between adjacent karst systems were smoothed, heads were calibrated and spring discharges were regulated by adjusting conduit system conductivities. The final average conduit network density is 2.6 km/km^2; the spacing of karst conduits is about 400 m. One-dimensional hydraulic conductivities of the conduits assuming laminar flow, vary between 0.1 and 30 m^3/s.

By applying this approach, the approximation of observed hydraulic heads and spring discharges for every spring became possible (Kovacs et al. 2002b) (Table 1). Simulated hydraulic heads over the fissured blocks are usually 3–8 m higher than over the bordering karst channels. These results agree with observations. Calculated water balance shows, that almost 90 % (1.15 m^3/s) of the total infiltration (1.32 m^3/s) exits the aquifer at observed karst springs. The rest feeds small springs, the alluvium, or directly surface streams. Because the catchment areas of the Beuchire and Doux springs extend outside of the model

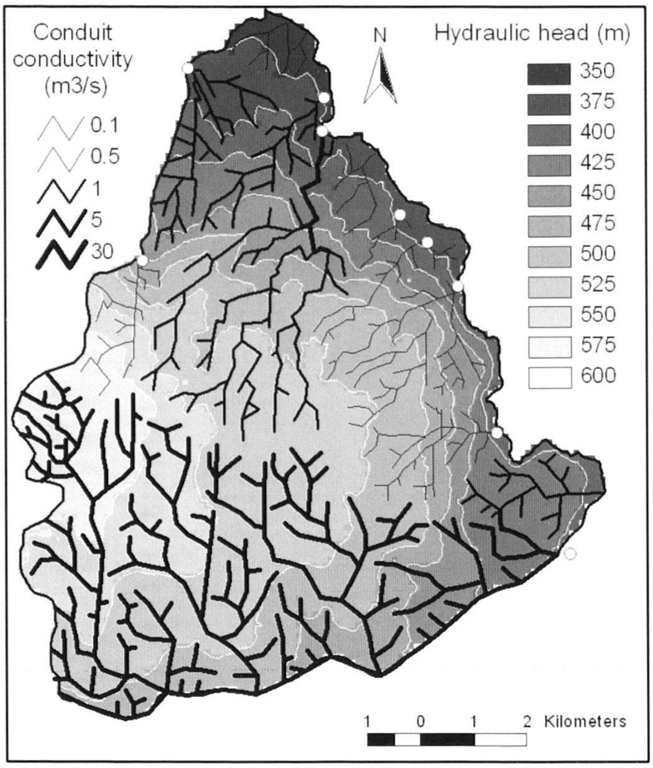

Fig. 16. Extended conduit network geometry and calculated hydraulic head distribution. Calibrated conduit conductivities are numerical values and refer to darcian flow conditions. White dots indicate spring locations.

domain, the calculated discharges of these springs are considerably less than measured values.

Model results clearly show that the calibration of water levels and spring discharges is not possible without extending the observed conduit network system to the entire model domain if one intends to abide by realistic hydraulic parameters. This illustrates that even in steady-state conditions the single continuum porous equivalent approach is not adequate to simulate groundwater flow in karst systems.

Flow simulations suggest the existence of extended karst conduit networks, each extending to or close to the catchment boundaries, having hydraulic conductivities proportional to the measured average spring discharges (Fig. 16).

5. Conclusions

This study presents a synthesis of hydrogeological data from the Bure plateau.

A detailed geometrical – hydrostratigraphic reconsideration of the research site was performed. A hydrostartigraphical map, cross-sections and structural surfaces have been constructed based on the most relevant data. Aquifer geometry and hydraulic boundaries were determined.

A summary of former tracing experiments was presented, the catchment boundaries were defined, and new subcatchments were established. One of the main achievements of this study was to clarify the hydraulic role of the Malm marl layers. Tracing experiments showed that the Sequanian and the two Kimmeridgian marl horizons do not act as aquicludes, and they do not significantly influence regional flow patterns.

Based on geometrical properties, piezometric observations, tracing tests and theoretical speculations, a coherent conceptual model of the Bure aquifer was constructed. On the basis of piezometric observations and aquifer geometry the maps of the average water table, saturated, and unsaturated zone thickness were constructed. Moreover, the possible extent of the shallow karst zone was estimated from the calculation of the minimum and average water tables. While the minimum water table calculated in this manner approximates the minimum hydraulic heads over the karst conduits, the average water table calculated from piezometric observations, approximates the average water levels over the fissured matrix.

These calculations located the regional groundwater divide along the Porrentruy – Bure – Croix axis, and designated extended shallow karst zones in the area of Buix and Croix.

A steady-state two-dimensional groundwater flow model was constructed, using the combined discrete channel and continuum approach, to quantitatively synthesize observations and assumptions, to approximate water table and flow field, and to test our ideas on the spatial configuration of the karst network and on the hydraulic properties of the aquifer.

Numerical simulations based on measured and realistic assumed hydraulic parameters suggest the existence of extended karst systems, each extending to the catchment boundaries. The hydraulic conductivity of each system is roughly proportional to its average discharge.

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