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**GEOGRAPHIC INFORMATION SYSTEMS ANALYSIS
OF GEOLOGIC CONTROLS ON THE DISTRIBUTION
OF DOLINES IN THE OZARKS OF SOUTH-CENTRAL
MISSOURI, USA**

UPORABA GIS (GEOGRAFSKI INFORMACIJSKI SISTEM)
ZA GEOLOŠKO POGOJENOST RAZŠIRJENOSTI VRTAČ
V OZARKIH, JUŽNO-OSREDNJI MISSOURI, ZDA

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Izvleček

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Randall C. Orndorff & David J. Weary & Kerry M. Lagueux: Uporaba GIS (geografski informacijski sistem) za geološko pogojenost razširjenosti vrtač v Ozarkih, južno-osrednji Missouri, ZDA

Geološki vzroki, ki pogojujejo razporeditev in razvoj vrtač na Salem planoti, Ozarki, južno-osrednji Missouri, ZDA, so bili statistično analizirani z uporabo GIS. Geološki vzroki predstavljajo litostratigrafijo, geološko strukturo, površje in globino do talne vode. Obravnavali so področje za točkovne podatke 2.613 vrtač na dveh 30' × 60' kartah s 30 m intervali. Izračunali so % pogostosti vrtač za pet litostratigrafskih enot, pri čemer so ugotovili, da je v Jefferson City dolomitu in Roubidoux formaciji največja gostota vrtač. Opravljena je bila analiza žariščne vsote sosedstva, da bi ugotovili, če ima razporeditev vrtač značilnost združevanja v skupine ali značilnost linearnosti, kar kaže na vpliv geološke strukture. Usmerjenost skupin vrtač na SZ se pojavlja vzdolž projekcije prelomne cone Bolivar-Mansfield v južno-osrednjem Missouriju. Večina vrtač na obravnavanem terenu se nahaja na območjih uravnanih in na položnih pobočjih, kar je pogostejše kot na močno razčlenjenih področjih. Močna razpokanost v bližini regionalnih prelomnih con lahko pospeši razvoj vrtač na planoti. Razumevanje kraškega sistema je pomembno za boljše urejanje uporabe zemlje v Ozarkih, vključno z ohranjanjem naravnih virov, urejanjem talne vode in varovanjem okolja, še posebno ker raziskani teren vsebuje možne ekonomsko ugodne zaloge Pb in Zn.

Gljučne besede: Kras, vrtače, GIS, planota Ozarki, Missouri, ZDA.

Abstract

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91:551.4:[659.2:681.3](77)

Randall C. Orndorff & David J. Weary & Kerry M. Lagueux: Geographic information systems analysis of geologic controls on the distribution on dolines in the Ozarks of south-central Missouri, USA

The geologic controls on the distribution and development of dolines in the Salem Plateau of the Ozark Plateaus Province, south-central Missouri, USA, was statistically analyzed by using a geographic information system. The controls include lithostratigraphy, geologic structure, slope, and depth to water table. Area and point data for 2,613 dolines in two 30' × 60' quadrangles were compiled on a 30-meter grid. The percent area of dolines was calculated for five lithostratigraphic units, and it was determined that the Jefferson City Dolomite and Roubidoux Formation have the highest density of dolines. A focal sum neighborhood analysis was performed to determine if the distribution of dolines had any clustering or linearity that may suggest structural control. A northwest alignment of doline clusters occurs along a projection of the Bolivar-Mansfield fault zone in south-central Missouri. Most dolines in the study area occur on the plateau areas and on gentle slopes rather than in the highly dissected areas. Intense fracturing near regional fault zones may enhance doline development on the plateau areas. An understanding of the karst system is important for better land-use management practices in the Ozarks, including conservation of natural resources, ground-water management, and environmental protection, especially because the study area includes potential economic lead and zinc mineralization.

Key Words: karst, dolines, geographic information system, Ozark Plateaus, Missouri, USA.

INTRODUCTION

Understanding the various geologic controls on doline development is important for at least two reasons. First, dolines can be locations for contaminants to enter the ground-water system. Second, there is a potential for doline collapse occur when hydrogeologic regimes change. In south-central Missouri (Fig. 1), contaminants enter the ground-water system through garbage dumps in dolines, agricultural run-off, leaky sewage lagoons, and mine tailings ponds. Collapse dolines caused by changes in hydrogeologic regimes have been documented in relation to impoundment of surface water in south-central Missouri (Aley et al. 1972). If these impoundments contain contaminants, then there is a high potential for ground-water contamination if collapse occurs.

This study concentrated on the Spring Valley and West Plains 30' × 60' quadrangles in south-central Missouri, USA within the Ozarks Plateaus Province (Fig. 1). The area contains one of the world's largest lead and zinc mining districts, the Viburnum Trend, and other potential lead and zinc deposits. Understanding the surface to subsurface interaction with karst waters is necessary to evaluate potential ground-water and surface-water contamination.

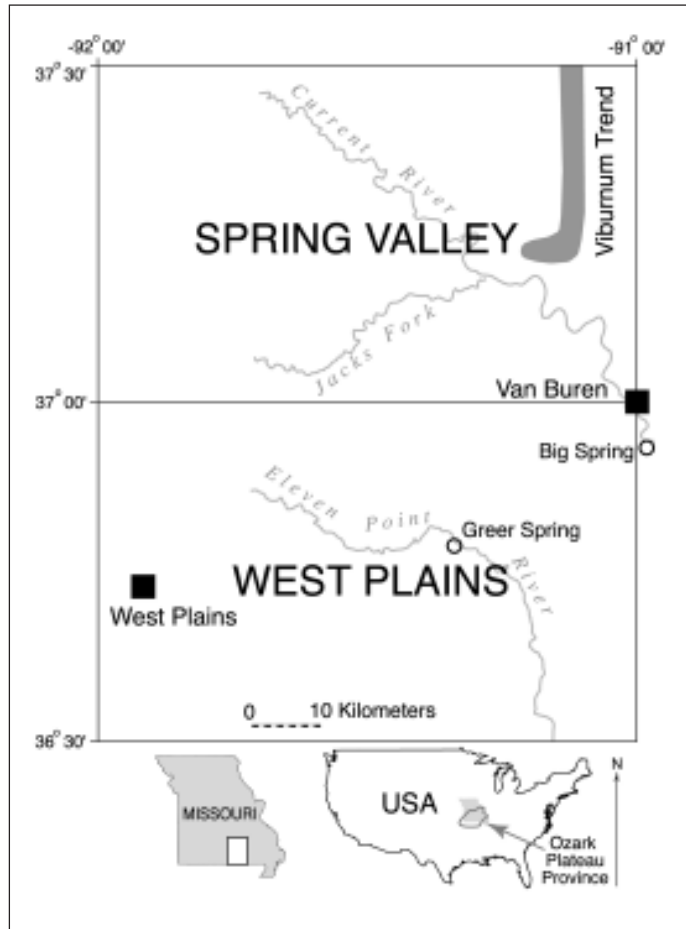


Fig. 1: Map showing location of study area (Spring Valley and West Plains 30' × 60' quadrangles). The Viburnum Trend is one of the world's largest lead and zinc mining districts.

Sl. 1: Karta, ki prikazuje položaj obravnavanega terena (karti Spring Valley in West Plains 30' × 60'). Viburnum jarek je eden največjih nahajališč Pb in Zn na svetu.

tion and delineate areas where dolines form. A geographic information system (GIS) was used to evaluate the distribution of dolines within the study area and to aid in the determination of geologic, physiographic, and hydrogeologic controls on the development of dolines. To test the possible controls on the formation of dolines, methods were developed using Arc/Info version 7.1.1¹ and Arcview version 3.2¹ to evaluate relationships between the distribution of dolines to stratigraphic units, possible fault zones, slope position, and depth to the water table.

GEOLOGIC SETTING

The study area is the Spring Valley and West Plains 30'×60' quadrangles in the Salem Plateau, part of the Ozark Plateaus Province of south-central Missouri (Fig. 1). About 750 to 900 m of gently dipping Upper Cambrian and Lower Ordovician dolomite, sandstone, limestone, shale, and chert overlie Middle Proterozoic rhyolite and granite (Fig. 2). Dolomite is the dominant lithology. Only the Potosi Dolomite and younger units are exposed in the study area. Middle Proterozoic basement rocks are exposed as knobs, upon which rocks as high as the Gasconade Dolomite were deposited.

The Ozark Plateaus Province is a large structural dome. In south-central Missouri, strata dip gently to the southeast. Locally, strata dip steeply away from Middle Proterozoic knobs and near fault zones. Faults trend to the northwest and northeast (Fig. 3) and are generally steeply dipping.

Distinctive karst features, including underground drainage, are abundant. Some of the largest springs in the United States are found in the area, including the two largest springs in Missouri, Big Spring (average flow of 12 m³/sec or 282 million gallons per day) and Greer Spring (8 m³/sec or 183 million gallons per day) (Fig. 1) (Vineyard & Feder 1982). All of the Ozark springs have large fluctuations in discharge related to variation in precipitation. Drainage is characterized by many losing and disappearing streams as well as extensive cave and conduit systems. In upland areas, dolines in the residual cover are common and collapse dolines have developed because of changes in the ground-water regime (Aley et al. 1972).

ANALYSIS OF DOLINES

Explanation of the Doline Database

The database of dolines was developed by compiling all dolines that are represented on the individual 7.5-minute topographic quadrangle maps by closed-contour depressions within the study area. Therefore, only dolines that cross a 20-ft contour on the topographic maps are included in the database. This was done to keep the database consistent over the entire study area.

Test of Randomness

The first analysis of the doline database was a test of randomness to determine if the distribution was random, clustered, or uniform. A fishnet with quadrat (equal-sized subareas) sizes of 1500

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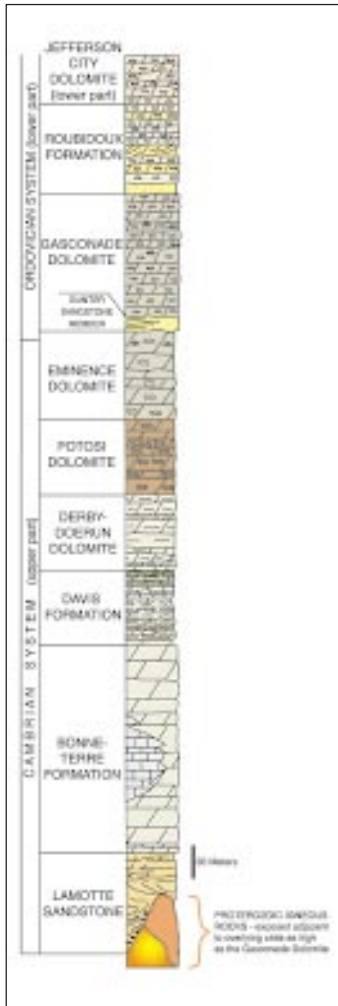


Fig. 2: Stratigraphic column of south-central Missouri.
Sl. 2: Stratigrafski stolpec južno-osrednjega Missourija.

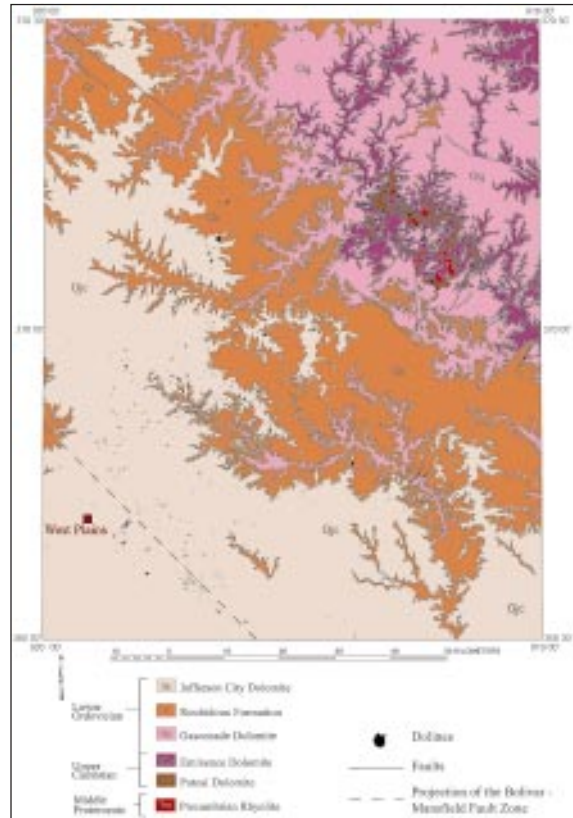


Fig. 3: Generalized geologic map of the study area.
Sl. 3: Generalizirana geološka karta obravnavanega terena.

m by 1500 m was placed over the distribution of dolines (Fig. 4) to compare the actual number of dolines per quadrat to the expected number per quadrat if the distribution was random. By using the equation in Figure 5 as a test of randomness, it was found that $m/T > s^2$ ($0.599 > 0.007$) and therefore the distribution is more uniform than random. Since the distribution was found not to be random, tests were performed to determine geologic, physiographic, and hydrogeologic controls.

$$S^2 = \frac{\sum_{i=1}^T (r_i - m/T)^2}{T-1}$$

Fig. 5: Equation from Davis (1986) used to compare actual distribution of dolines to expected distribution of dolines. s^2 , test statistic; r , number of dolines per quadrat; m , total number of dolines; T , total number of quadrats; m/T , expected number of dolines per quadrat. If $m/T > s^2$ then the distribution is more uniform than random. If $m/T = s^2$ then the distribution is random. If $m/T < s^2$ then the distribution is more clustered than random.

Sl. 5: Enačba iz Davies-a (1986) uporabljena za primerjavo realne razporeditve vrtač s predvideno razporeditvijo vrtač. s^2 = statistični test, r = število vrtač v enem kvadratu, m = število vrtač, T = število vseh kvadratov, m/T = predvideno število vrtač v enem kvadratu, če je $m/T > s^2$, potem je razporeditev bolj uniformna kot naključna, če je $m/T < s^2$, potem je razporeditev bolj združena v skupine kot naključna.

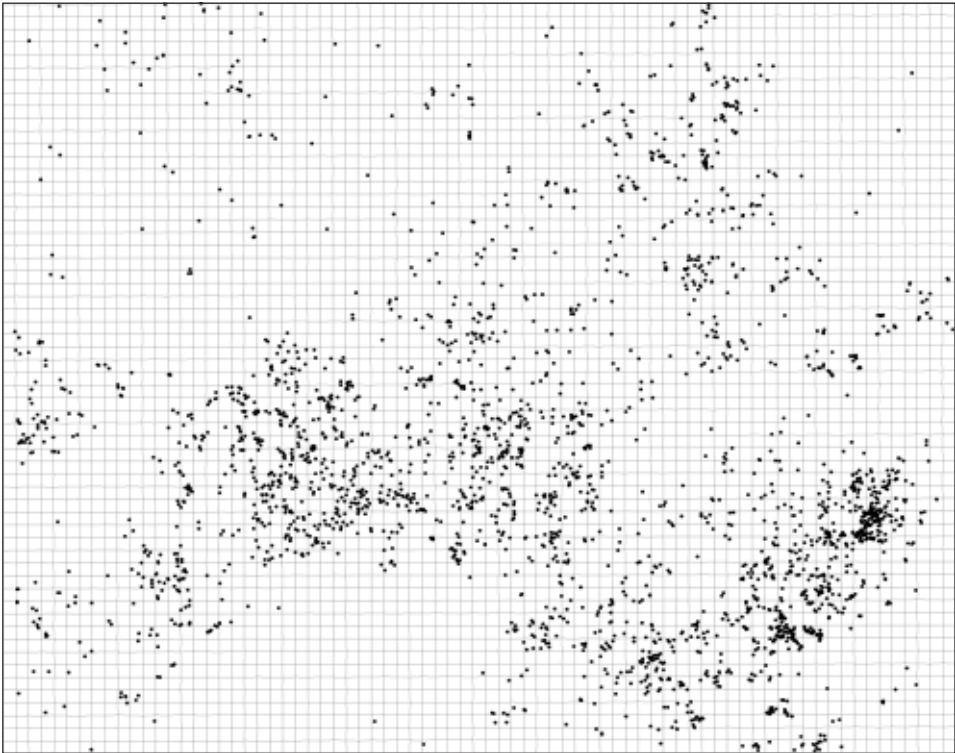


Fig. 4: Doline point data for the Spring Valley and West Plains $30 \times 60'$ quadrangles showing fishnet with 1500 m by 1500 m quadrats used for test of randomness.

Sl. 4: Točkovni podatki za vrtače na kartah Spring Valley in West Plains $30 \times 60'$, ki kažejo mrežo s kvadrati $1500 \times 1500 \text{ m}$, kar so uporabili za test naključnosti.

Relationship of Doline Distribution to Lithologic Unit

The doline database was overlain on the geologic map of the study area to see if the uniform distribution was related to lithologic units (Fig. 3). The GIS was used to calculate the percent area of each formation that contained dolines (Fig. 6). For the entire study area dolines covered 0.41 percent of the Jefferson City Dolomite and 0.25 percent of the Roubidoux Formation. All other lithostratigraphic units have much

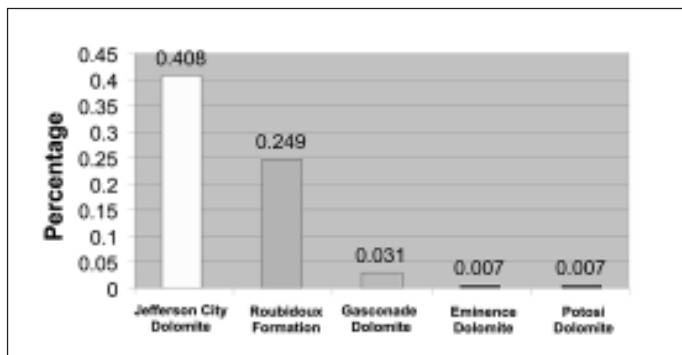


Fig. 6: Histogram showing percent area of dolines per lithostratigraphic unit.

Sl. 6: Histogram, ki prikazuje % območij vrtač na litostratigrafsko enoto.

lower percentages. Any lithostratigraphic control may be related to the fact that these two units crop out on the plateau areas and generally have a thick residual cover.

Relationship of Doline Distribution to Structure Using a Focal Sum Neighborhood Analysis

A focal sum neighborhood analysis uses the database to determine areas of high concentrations of dolines. This analysis aids in determining areas with higher susceptibility to doline development and helps identify patterns in the doline distribution.

A grid with 30 m by 30 m cells was overlain on the doline database. The 30 m by 30 m cells were used to keep the analysis consistent with the resolution of the digital elevation model (DEM). Any cell that contained area within a doline was given a value of one and cells that did not contain any area within a doline were given a value of zero (Fig. 7). The GIS calculated for each cell the number of cells in a 50 by 50 block around it that contained a value of one (Fig. 8). That value was then assigned to that cell as the focal sum (Fig. 9). By evaluating the mean of the focal sums for each cell, areas of high concentrations of dolines become apparent (Fig. 10). On Figure 10, the red areas show high concentrations of dolines.

Visual examination of the clusters shows some linearity to the distribution of dolines, especially in the southwestern part of the study area near West Plains. Linearity may suggest structural control to the distribution of dolines, at least in the West Plains area. Faulting in the study area shows northeast and northwest trends that parallel the linearity of the doline distribution (fig 3). The northeast and northwest trends are inherent Precambrian structural trends in the state of Missouri and faults that cut Cambrian and Ordovician strata are probably reactivated Precambrian structures. Also, the northwest trending Bolivar-Mansfield fault zone in central Missouri projects into the West Plains area (Fig. 3). However, lack of outcrops due to a thick residual cover does not

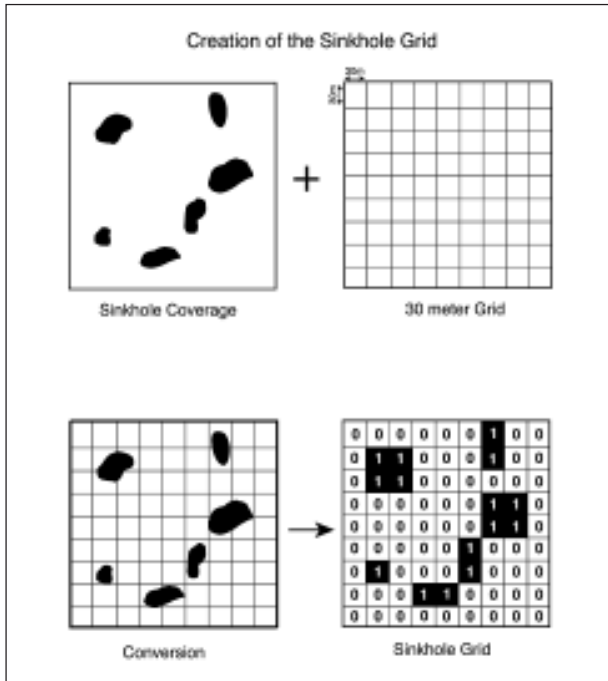


Fig. 7: Diagram showing an example of how the GIS created a sinkhole area coverage for the focal sum analysis. Note: this example uses a 7 by 7 block; actual analysis used a 50 by 50 block. Diagram not to scale. See text for explanation.

Sl. 7: Diagram, ki kaže kako GIS ustvari pokrov za območja vrtač za analizo žariščne vsote sosedstva. Opomba: ta primer uporablja 7 × 7 blok, realne analize uporabljajo 50 × 50 blok. Diagram ni v merilu. Glej članek za razlago.

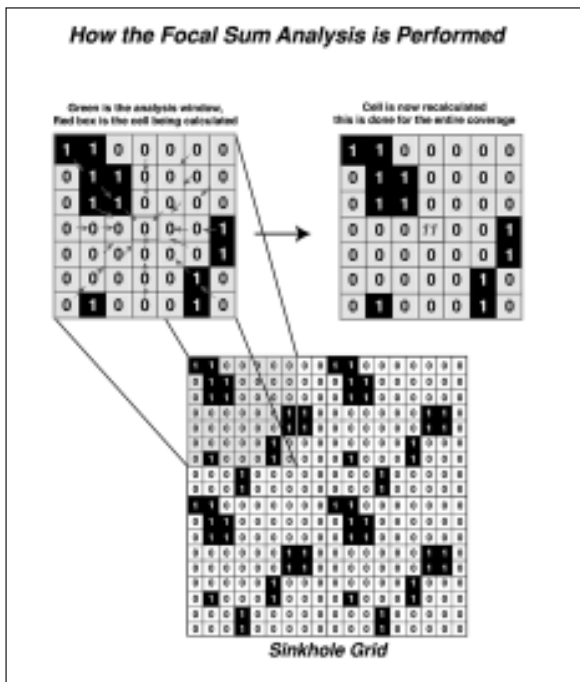


Fig. 8: Diagram showing an example of how the GIS calculated the focal sum. Note: this example uses a 7 by 7 block; actual analysis used a 50 by 50 block. Calculations of focal sums for cells around the border uses smaller analysis windows to incorporate the lack of data. Diagram not to scale.

Sl. 8: Diagram, ki prikazuje kako GIS izračuna analizo žariščne vsote sosedstva. Opomba: ta primer uporablja 7 × 7 blok, realne analize uporabljajo 50 × 50 blok. Izračuni za analizo žariščne vsote celic na robju uporabljajo manjše analize oken za vključitev manjkajočih podatkov. Diagram ni v merilu.

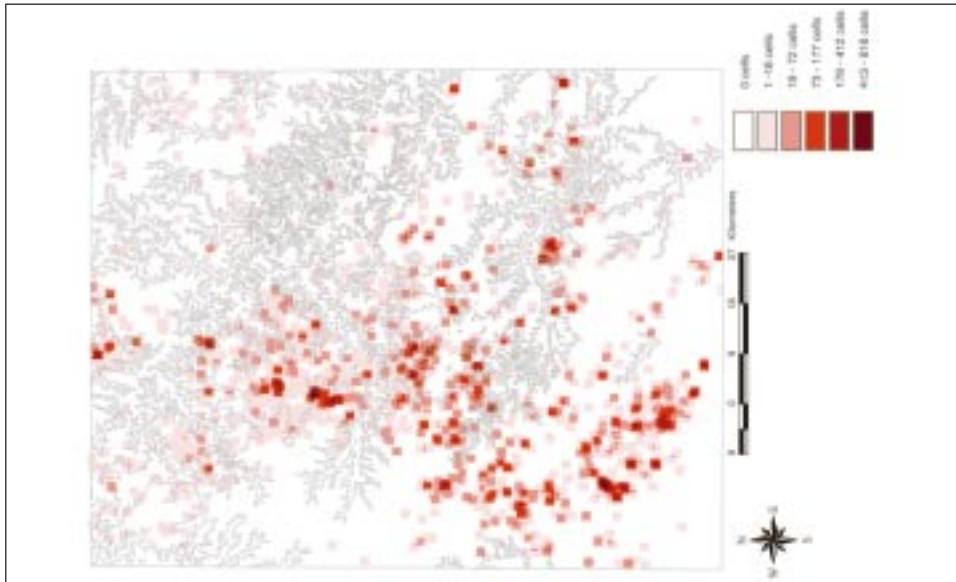


Fig. 9: Map of the Spring Valley and West Plains 30'x60' quadrangles showing 50 cell by 50 cell focal sum neighborhood analysis.

Sl. 9: Karta Spring Valley in West Plains 30'x60', ki prikazuje celice 50x50 za analizo žariščne vsote sosedstva.

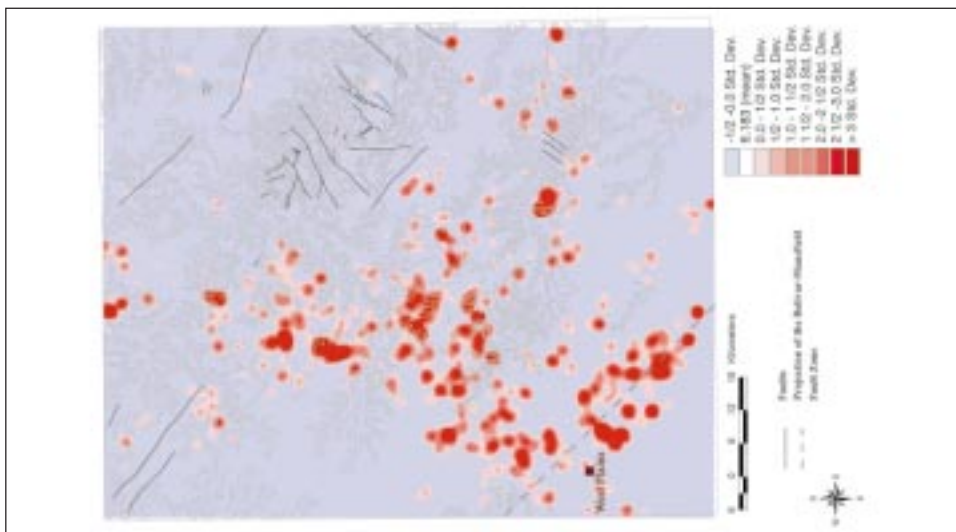


Fig. 10: Map of the Spring Valley and West Plains 30'x60' quadrangles showing 50 cell by 50 cell focal mean of the focal sum. Mean equals 6.183.

Sl. 10: Karta Spring Valley in West Plains 30'x60', ki prikazuje celice 50 x 50. Povprečen ustreza 6,183.

allow for surface examination of the fault zone in the West Plains area. Joint trends in the West Plains area are more scattered than the regional joint trends and show a secondary set of joints parallel to the Precambrian trends (Fig. 11). Increased fracturing and faulting along a projection of the Bolivar-Mansfield fault zone in the West Plains area is probably responsible for the high concentrations of dolines and the linearity of the clusters.

Relationship of Doline Distribution to Slope

Slope categories were calculated from the 30 m digital elevation model (DEM) of the study area (Fig. 12). A slope map was generated using this DEM by calculating the differences in elevations (Fig. 13). A grid with 30 m by 30 m cells containing dolines was overlain on the DEM and degree of slope assigned to each cell. The GIS was used to calculate the area of dolines as related to these slope categories. Predominantly, dolines are developed on slopes of 0 to 3 degrees (Fig. 14) and mainly on the plateau areas. Since the dolines are developed in residuum, this relationship can be expected. Residuum is best developed and thickest on the plateau areas, whereas hill slopes tend to be covered with colluvium and stream valleys with alluvium. A small number of dolines occur on hill slopes and in the valleys, however, mass movement of materials and stream processes may obscure the expression at the surface of many others.

Relationship of Doline Distribution to Depth to Water Table

By subtracting the potentiometric surface map (Fig. 15) from the DEM (Fig. 12) of the study area, a map of the depth to the water table was produced (Fig. 16). The doline database was overlain on this map and the area of dolines compared to depth to water table. Figure 17 is a graph showing the relationship between the depth to the water table and area of dolines. The data was percent normalized to correct for sampling bias by multiplying the area of dolines per depth class by the reciprocal of the percent of the total area represented by each water depth class. Although the highest percentage of the area has a depth to water table of 31 m,

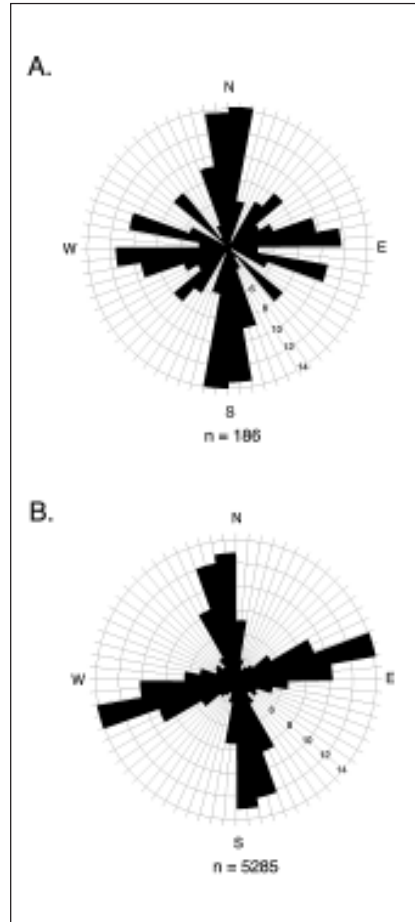


Fig. 11: Compass-rose diagrams of, A) joints along the Bolivar-Mansfield fault trend in the West Plains area, and B) regional joint trends. Numbers on diagrams is percent of total.

Sl. 11: Rozeta. A) razpoke vzdolž preloma Bolivar-Mansfield na področju West Plains in B) regionalne smeri razpok. Številke na diagramih so v % skupne vrednosti.

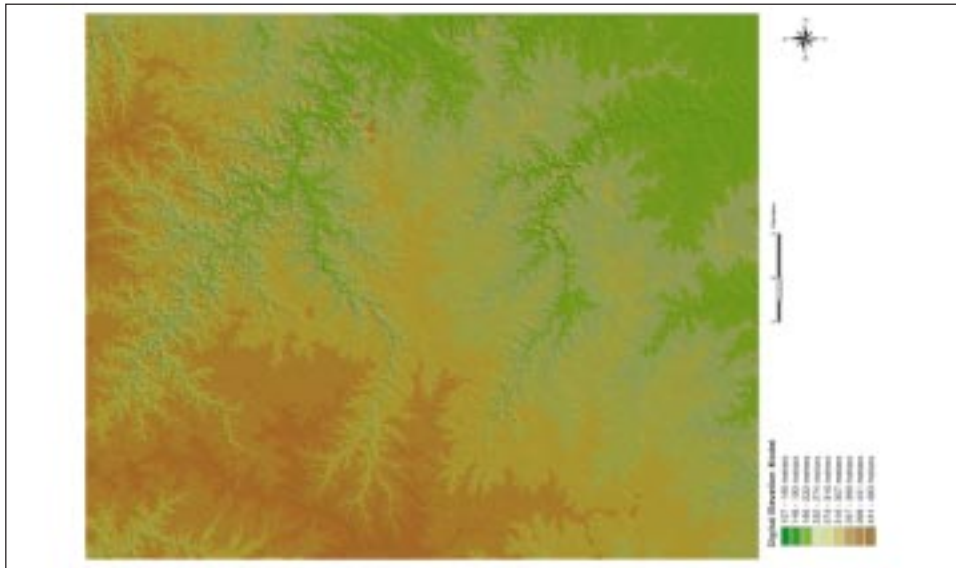


Fig. 12: Digital elevation model for the Spring Valley and West Plains 30'x60' quadrangles. A Digital Elevation Model is a digital file consisting of terrain elevations for ground positions at regularly spaced horizontal intervals.

Sl. 12: Digitalni model reliefa (DMR) za karti Spring Valley in West Plains 30'x60', to so digitalni podatki, ki vsebujejo višine reliefa pri določenih prostorskih horizontalnih intervalih.

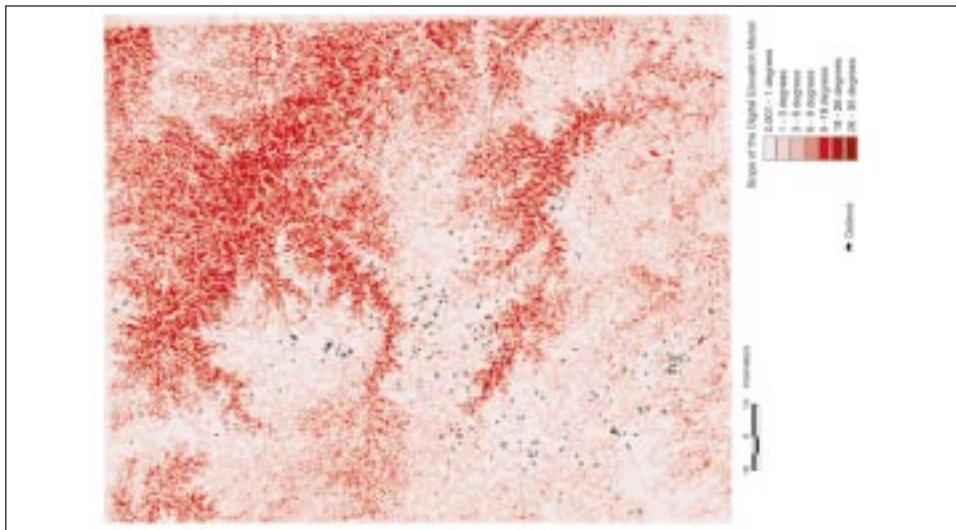


Fig. 13: Slope map generated from digital elevation model showing dolines.

Sl. 13: Karta pobočja iz DMR, ki prikazuje vrtače.

Fig. 14: Histogram showing percent area of dolines per slope category.

Sl. 14: Histogram, ki prikazuje odstotek vrtač glede na pobočno kategorijo.

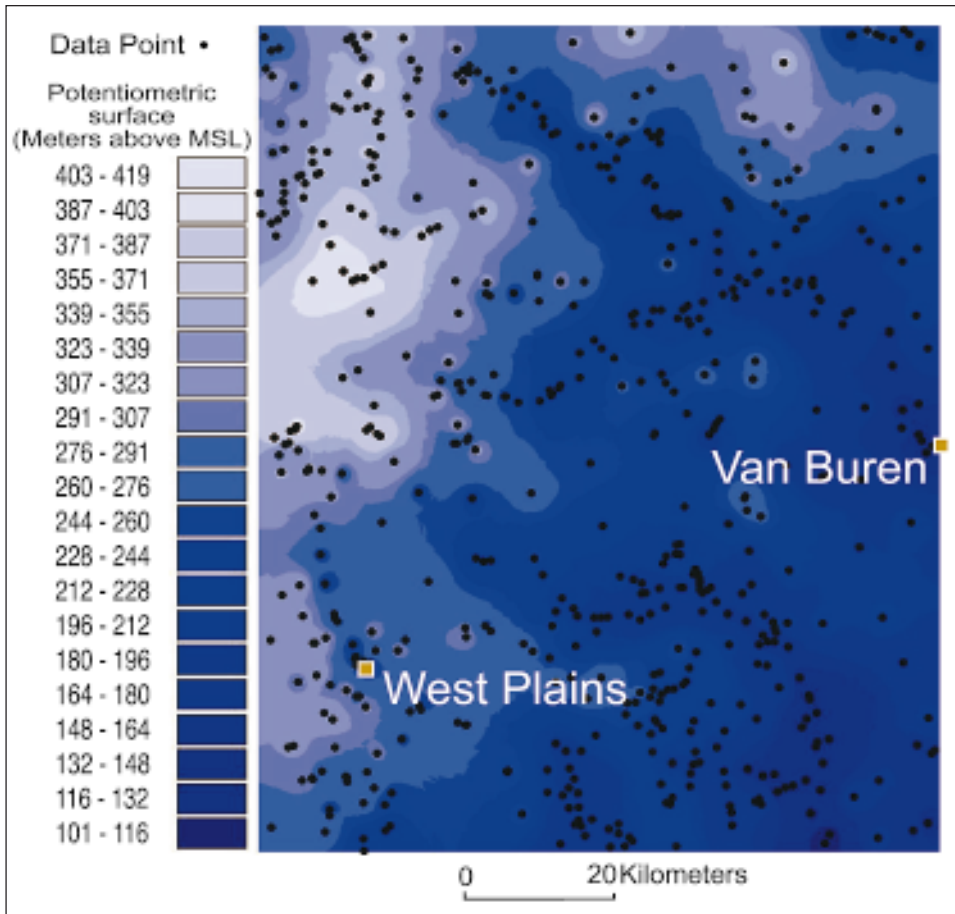
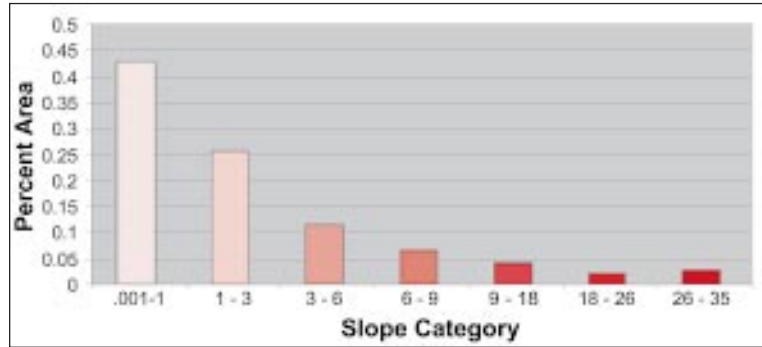


Fig. 15: Potentiometric surface map for the Spring Valley and West Plains 30'x60' quadrangles.

Sl. 15: Površinska karta verjetnih višin za Spring Valley in West Plains 30'x60'.

doline area increases with depth to water table to at least 178 m. Below 178 m, the data is not statistically reliable due to lack of data. This suggests that the deeper the water table, the more susceptible the area is to doline development. This relationship may be due to more void space in a thicker vadose zone to transport material.

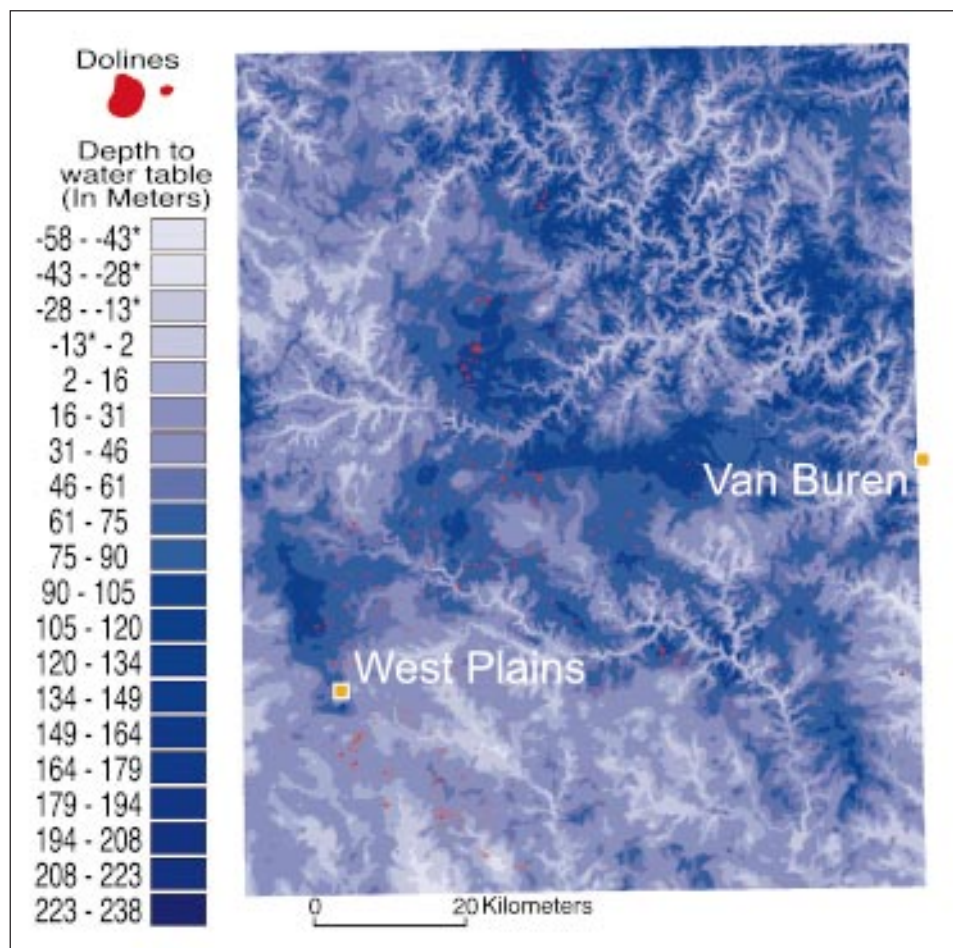


Fig. 16: Depth to water table below surface produced by subtracting the potentiometric surface from the DEM. Negative values in depths to water table are an artifact of subtracting the potentiometric surface, which is not well constrained, from the DEM which is well constrained.
Sl. 16: Globina do talne vode pod površjem določena z odbitkom verjetnih višin površja iz DMR. Negativne vrednosti globin podtalnice so določene z odbitkom od verjetnega površja, ki ni dobro stisnjen, od DRM, ki je dobro stisnjen.

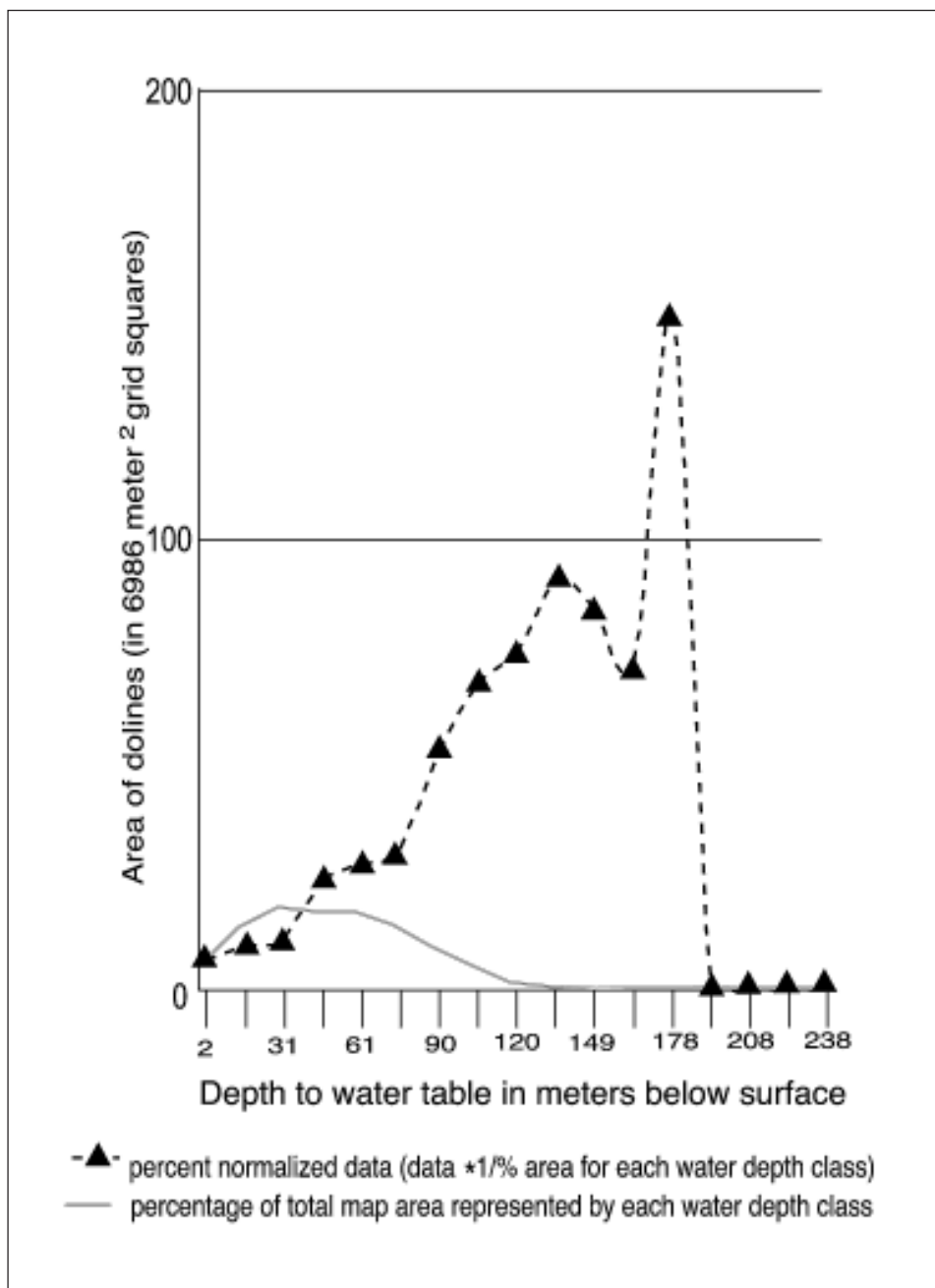


Fig. 17: Graph comparing the area of dolines to percentage of area of depth to water table.
 Sl. 17. Graf, ki primerja področja vrtač z odstotkom področij globine do talne vode.

CONCLUSIONS

Using a GIS, doline distributions can be compared to various geologic, physiographic, and hydrogeologic parameters to determine possible controls on their development. For an area in the Ozark Plateaus Province of south-central Missouri, USA, it was found that the distribution of dolines is not random. Lithostratigraphically, the Roubidoux Formation and Jefferson City Dolomite are the geologic units with the most dolines in the plateau area, however, dolines are concentrated along major structures such as fault zones. A relationship between the depth to the water table and increased doline development is also suggested. Statistical analyses, such as a focal sum neighbor analysis, can aid in defining areas of high concentrations of dolines and help to generalize areas with greater potential for ground-water contamination and susceptibility to doline collapse.

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UPORABA GIS (geografski informacijski sistem) ZA GEOLOŠKO POGOJENOST RAZŠIRJENOSTI VRTAČ V OZARKIH, JUŽNO-OSREDNJI MISSOURI, ZDA

Povzetek

Z uporabo GIS-a lahko razporeditev vrtač primerjamo z različnimi geološkimi, fiziografskimi in hidrogeološkimi parametri, ki so lahko vzrok za nastanek vrtač. Za področje planote Ozarkov v južno-osrednjem Missouriju, ZDA so ugotovili, da razporeditev vrtač ni naključna. V litostratigrafskem smislu sta formacija Roubidoux in Jefferson City dolomit geološki enoti z največ vrtačami na področju planote, hkrati so vrtače koncentrirane vzdolž glavnih struktur kot prelomnih con. Odnos med globino talne vode in povečanim številom vrtač je tudi možen. Statistične analize kot analiza žariščne vsote sosedstva, lahko pomagajo pri določitvi področij z visoko koncentracijo vrtač in lahko pomagajo generalizirati področja v večjo možnostjo onesnaženja podtalnice in sprejemljivostjo za nastanek udornic.