Adapting SWAT for the Assessment of Thinly-Soiled Karst and Sinkhole features

REPORT

A patterned ground sinkhole located on Church Rd., Leroy, New York

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ABSTRACT

Thirty karst features were ranked for protection by extracting their watershed divide area and dividing by the area covered by thin soils in order to calculate an index for gauging their sensitivity to groundwater contamination. The study was conducted on the Onondaga escarpment in western New York in an area that has suffered several well contamination events in the past. In this report, we discuss the performance of two automated watershed delineation algorithms for performing this analysis. The approaches were tested against the "true" watershed divide mapped in the field to determine if these automated approaches can be successfully employed in this landscape, which consists of a heterogenous mixture of thinly-soiled karst, sinkholes, and glacial features such as end moraines, ground moraines, channels and other till deposits. The two automated approaches can be considered to be at opposite ends of the spectrum in their treatment of internally-drained and zero slope regions. The Jensen and Domingue algorithm removes depressions to insure flow continuity. Its catchment delineation is thus inclusive, however, it has been known to develop unrealistic watershed divides in areas of flat or low-sloped topography. The PCSA does not remove depressions and assumes that all breaks in flow are hydrologically realistic. Its delineation tends to be more conservative and excludes areas that are zero-sloped and are isolated by depressions. It allows multiple flow directions however, which can sometime create hydrologic continuity where it doesn't exist. The results suggest that both approaches had issues which occasionally caused inaccurate watershed delineation. The Jensen and Domingue algorithm performed well in areas dominated by convergant flow, however it was difficult to apply to linear karst features where flow was down straight hillslopes. Both approaches had issues with road berms, ditches and culverts which led to inaccurate watershed delineation. Catchment / Effective areas indices ranged from 621 to 1 with smaller solution sinkholes have the highest indices. Despite their issues, both automated methods performed well in ranking the sites, with Spearman's Rho coefficients of 0.95 and 0.93 for Jensen and Domingue and PCSA respectively. Road berms, drainage ditches and culverts changed the effective size of several of the watersheds. These features tend to decrease the effective size of the catchment, however, they can also be a source for runoff and pollutants. Work continues on the final step of our project which is to model all of these catchments with SWAT in order to estimate the flux of nutrients into the groundwater table at each site.

INTRODUCTION

Thinly bedded karst areas have proved to be very sensitive to groundwater contamination in New York State. For example in western New York, the county of Genesee has experienced three major well contamination events. Besides the health and safety issues which are significant, these events cost the tax payers money as public water often needs to be piped into home owners after the sites are cleaned up. In areas, where bedrock is close to the city, this process can be expensive. Well contamination events have led a committee of scientists (see Czymmek and Geohring, 2004; Czymmek et al, 2011) to re-evaluate the fertilizer management guidelines in areas of thinly-soiled karst. This committee has stressed the need to recognize and locate where these features are so that they may be protected from excessive fertilizer applications. Two recent studies (Reddy and Kappel, 2010 and Richards et al, 2010) have been carried out to find where these sensitive areas are. The former mapped structures and developed detailed isopach and geology maps for identifying areas of concern. They also compiled known sinkhole sites from interviews with local experts. The latter mapped sinkholes from aerial photography and fracture traces, and assessed sixty sites in the field. This study identified 39 sites of concern in Genesee county and the area east to Caledonia. These works are important steps forward, but a rational approach needs to be developed for ranking these sites in order of their sensitivity to groundwater pollution. In this way they can be prioritized for management. This study adapts a widely used hydrologic model (ArcSWAT) to rank these features by assessing their catchment area and estimating the flux of nutrients they receive. This study will also test the accuracy of two different digital terrain algorithms for defining watersheds in the study area, which contains multiple scales of depressional topography caused by glacial weathering and karst formation processes.

BACKGROUND

Karst areas are known for their agricultural productivity. However, karst watersheds are vulnerable to surface and groundwater contamination because of complex surface-water/groundwater interactions, including dissolution fast pathways to the subsurface. This is important because approximately 20% of the U.S. (40% of the eastern U.S.) is karst (Quinlan 1989) and agricultural runoff is one of the major causes of surface-water contamination in the United States (USGS, 1999). The Onondaga FM is a known karst lithology in NYS that is heavily farmed and is an important aquifer for domestic water supplies. In the past five years there have been 3 major well contamination events that have been attributed to agricultural activities in karst areas. The most recent occurred in January, 2010 when several domestic wells were contaminated at the front of the Onondaga Escarpment. This and the previous two events all occurred in areas containing thin soils. Two of the events occurred during periods of snowmelt and frozen soils. The most recent event occurred not far from a karst feature mapped by Richards et al, 2010. Recent studies have demonstrated that thinly-bedded karst sites could be identified from fracture trace maps and field surveys. A technique needs to be developed to rank these sites in terms of their probable impact on the groundwater table. This study applies the model SWAT to evaluate the nonpoint source pollution from the catchment area of these sites, in order to determine their impact to the water table. Once a model like this is developed, experiments can be conducted to determine how agricultural activities can be managed to minimize nutrient pollution to these sensitive areas. CAFO operations do not typically have the resources to store their animal wastes over long periods of time. It is unrealistic to implement guidelines that completely forbid the application of animal waste. It is better to use models to time the delivery of fertilizer application to minimize groundwater impacts.

Richards et al (2010) surveyed sixty suspicious areas in and classified them into six different types based on their geology (**Figure 1a)**. These types include, large collapse features called "solution sinkholes", pattern ground sinkholes (**Figure 1b**), fractured bedrock areas, glacially enhanced sinkholes, glacial depressions and anthropogenic features. Of these types, the former three were evaluated to be the most sensitive to agricultural activities. Many of these sites are large areas of numerous smaller karst features and shallow fractured bedrock which causes the site to be under-drained. For example, fracture traces in the Leroy / Caledonia area tend to be populated by many small karst features and where covered by thin soils, ought to be considered sensitive to runoff from all sources that intersect them. Thus, from the management point of view we need to be concerned about agricultural activities in the drainage area of the entire fracture trace, not just the catchment areas of individual karst features.

A challenge to delineating catchments of karst features in western NY, is the low relief of the topography and the numerous depressions and zero slope areas that cover the area. This is the result of the areas long history of karst (Palmer, 1991) and glacial erosion processes (Fairchild, 1909). The region is known to contain glacial features such as end moraines, ground moraines, kames, kettles, channels and other till deposits (Muller, 1977). Many of these features contain small depressions which may be confused with the depressions caused by karst processes. Compounding this problem are road berms (**Figure 1c**), culverts and agricultural ditches which change surface flowpaths and can turn portions of the landscape into defacto detention basins. These anthropogenic features need to be accounted for in assessing the catchment areas and flow paths associated with karst features. These features may divert runoff away from thinly soiled karst areas, but may also be a source of pollution through stormwater inputs (Kemmerly, 1981; Fisher et al, 1993; Hubbard and Balfour, 1993).

SWAT (Arnold et al, 1998) is a hydrologic model that can be used to evaluate the impact that land use, agricultural management practices have on nonpoint source pollution. It is a popular model because it contains realistic parameterizations for dealing with snowmelt, groundwater, evapotranspiration and instream chemical and sedimentation processes. It also has a built in routine for testing the effectiveness of watershed buffering. SWAT has been used successfully in many TMDL, sedimentation and watershed management studies (Bingner et al, 1997; Fitzuh and Mackay, 2000; Spruill et al, 2000; Reunsang et al, 2005; Larose et al, 2006; Geza and McCray, 2007; Barlund et al, 2007; Easton et al, 2007; Hu et al, 2007; Tolson and Shoemaker, 2007; Wu and Johnson, 2007; Bosch, 2008; Kliment et al, 2008; Richards et al, 2011). It is attractive for our application because fertilizer and tillage activities can be precisely scheduled. And since it contains parameterizations for dealing with runoff on frozen soils (a phenonmenon that has been suggested to contribute to groundwater contamination in two of the last three well contamination events) will provide us with realistic, relevant information. It could also allow us to model the fluxes received by multiple karst features simultaneously, if these features correspond to the position of model outlets. The version of the model we are using is called ArcSWAT, which allows the quick preparation of model input files from GIS data. The problem with applying ArcSWAT in karst areas of low relief is that the resulting network of model channels and outlets will probably not coincide with the overland flowpaths and karst features we are trying to model. These features are problematic to model with ArcSWAT because the preprocessor in ArcSWAT utilizes the Jenson and Dominigue algorithm for preserving flow continuity. This process involves itteratively filling sinks (depressions) in the digital elevation model in order to obtain a model that can be analyzed to produce a catchment. This effectively removes many depression features which are probably real. This process may also cause misalignment of overland channels with zones of high flow accumulation. This makes it difficult to realistically classify channel cells. And for karst features with broad areas of low relief, such as fractured bedrock and pattern ground sinkhole sites, it will produce exceedingly low flow accumulations in the feature of concern. This will makes it difficult to insure connectivity of the flow to the site. These issues mean that outlets won't be snapped to karst features in a traditional ArcSWAT model and that model channels are unlikely to intersect them. To overcome these issues we defined watersheds separately from SWAT and employ user-defined basins in order to insure that model catchments are realistic. Once the SWAT model was created, the flux of nutrients flowing into thinly soiled karst areas was estimated and then divided by the area of thinly-soiled karst. The resulting mathematical index, analogous to a leaching index, was used to prioritize the sinkhole sites for management (**Figure 2**).

METHODOLOGY

Thirty suspicious karst features were evaluated in this study (**Table 1**). These sites are all sites that are classified as 'Solution sinkholes", 'Patterned ground sinkholes", "Glacially enhanced sinkholes" or "Exposed bedrock" and thus represent the sites that are most likely to be sites of concern. The "effective area" of each karst feature was mapped in the field using a GPS unit, aerial photographs, and utilizing available soil and GIS information. This zone is defined as the area associated with the feature in which all runoff that reaches it is assumed to be lost to the surface via fractures. For solution sinkholes in thickly-soiled areas, this is likely to be the area of the collapse structure itself. For zones covered by soils mapping units deemed by Czymmek et al (2011) as thin (< 40 inches), this is the area that encloses the soil mapping units. For pattern ground sinkholes, this is the area of the landscape that contains all sinkhole depressions and popup ridges. For exposed bedrock areas, it is the area of the landscape that contains exposed bedrock, or evidence of exposed bedrock, such as sub angular limestone clasts, tree roots bringing up bedrock, shallow soils, and elevated bedrock sites denoted on the Genesee County soil survey. It should be noted that for all of these types of sinkholes, "thin soils" are commonly located outside of the actual karst feature. For these instances, the effective area is expanded to include these areas.

Watersheds were delineated for the effective area of each karst feature by hand and using two automated approaches. The true catchment area associated with the effective area of the karst feature was evaluated in the field using contoured aerial photographs as follows. A one meter contour map superimposed on aerial photography was used to create a preliminary watershed divide using onscreen digitizing techniques in ArcGIS. This map was printed out and brought into the field and checked for accuracy. Culverts were digitized and roads with high road berms were identified. If it was determined that road berms would significantly impact surface drainage, watershed divides were adjusted to account for these obstacles. Channels and ditches were also digitized if they appeared in the field or in aerial photographs. Evidence of shallow bedrock such as abundant limestone clasts, in situ bedrock and depressions were located and noted. Maps were then taken back from the field and shapefiles of effective areas, watershed divides, channels and culverts were prepared.

The two automated approaches employed are the Jensen and Domingue (JD) approach (Jensen and Domingue, 1988) and the PCSA algorithm (PCSA; Richards and Brenner, 2004). These two automated approaches can be considered to be at opposites end of the spectrum in their treatment of internally drained regions. The Jensen and Dominigue algorithm removes depressions to insure flow continuity. Its catchment delineation is thus very inclusive, however, it has been known to develop unrealistic watershed divides in areas of flat or low-sloped topography . The PCSA does not remove depressions and assumes that all breaks in flow are hydrologically realistic. Its delineation tends to be more conservative and excludes areas that are zero-sloped and are isolated by depressions. The same 10 meter DEM was used to implement both digital terrain algorithms. In the case of the JD method, the DEM was "filled" to insure flow continuity and cells located on streams were adjusted to insure they would have high flow accumulation values by reducing the elevation of the cell. It was discovered for certain geomorphic situations, such as broad karst features located on the side of straight hillslopes, repeated runs of the JD algorithm on artificial channels had to be employed to obtain reasonable results. For the PCSA the DEM was not modified, and initial contributing areas were set to be all areas within 30 meters of the effective area of the karst feature plus any channels that intersect it. The PCSA algorithm was run for 300 itterations, meaning that it evaluated all areas within 3 km of the effective area of the karst feature.

A SWAT model was developed for the catchments defined above using ArcSWAT. This model made use of calibration parameters and nutrient management scenarios already developed from the Oak Orchard SWAT model (Richards et al, 2010). This watershed contains similar land use and farming strategies and is directly adjacent to the study area. Fluxes were calculated to determine the flux of phosphorus and nitrogen that makes it into the effective area associated with each karst feature. This flux was divided by the effective area of the karst feature to create an index that describes the features propensity to deliver nutrients to the water table. A total of 30 features in the Richards et al 2010 study were ranked using this index.

RESULTS

There was quite a bit of variability among the catchments associated with karst features. Watershed areas ranged in size from very small (0.1) to very large (35.9) sq km, depending on how well-connected the feature is to the hydrography network. **Figures 3** through **31** show maps of the effective area, true watershed divides, PCSA watershed divides and JD watershed divides of the karst features evaluated in the study. Artificial drainage ditches impacted 6 of the 30 sites (sites 1, 2, 3, 15a, 17, 53). In all cases these features increase the effective size of the catchment. Road berms impacted 20 of the 30 sites (sites 1, 2, 3, 9, 11, 15, 15a, 17, 18,19, 19a, 21, 27, 39, 42, 45, 45a, 53, 55, 58). In most cases these features reduced the effective size of the catchment. Cropland within catchments varied from 12.7% to 89.8% (**Table 1**). Inspection of the results suggest that the automated watershed delineation approaches had issues which occasionally caused inaccurate watershed delineation. The Jensen and Domingue algorithm performed well in areas dominated by convergant-flow (see **Figures 16, 28, 29**) however it was difficult to apply to linear karst features where flow was down straight hillslopes (Sites 11, 20; **Figures 8, 15**). In the case of site 11 it had to be applied three times in order to obtain meaningful results. The PCSA approach commonly included areas outside of the true watershed, causing it to overestimate the size of the watershed (see **Figure 11** for an example). This was caused by the multiple direction assumption, which includes flowpaths from topographic highs areas outside of the watershed that are unlikely to exist. Both approaches do not account for road berms, ditches and culverts which led to inaccurate watershed delineation. The former features commonly reduced the effective size of the catchment area.

Catchment / effective area ratios can be used as a proxy for nutrient loads (see **Figure 2**). A karst feature with a high catchment/effective area ratio will likely receive a large nutrient load that recharges in a small area. A karst feature with a small catchment / effective area ratio will receive a smaller nutrient load that recharges over a large area. From the standpoint of groundwater contamination, the former has a greater chance to introduce pollutants into the water table. These indices can be used as a rational approach to rank the sites for management purposes since sites with high catchment / effective area ratios may need buffering or other BMPs. Catchment / Effective areas indices ranged from 621 to 1 with smaller solution sinkholes have the highest indices. A comparison of ranks using all three watershed delineation methods suggests that they are comparable; Spearman's Rho coefficients between the true watershed and JD method and the true watershed area and PCSA were 0.95 and 0.93 respectively. So while the two automated watershed delineation methods had errors, the errors did not appear to impact the accuracy of the total area of the catchment. A ranking of these watersheds from most susceptible to groundwater pollution to least susceptible to groundwater pollution is presented below in **Table 2**. This was determined by dividing the true watershed area by the effective area of each watershed. Based on this analysis, the three most problematic sinkhole sites are site 23, the swallet located at the first fairway of the Leroy Country Club, site 54, and site 34, the Quinlan Rd sinkhole. The former and the latter experience occasional karst-related flooding (Richards, 2007; Voortman and Simons, 2009) and should be considered sites of special concern. Sites 9 and 10 were found to contain no compelling evidence of shallow bedrock, either in the field or from soil survey data which suggests that all soil mapping units have profiles greater than 40 inches. An interview with a knowledgeable landowner revealed the depth to bedrock in the area is greater than 3 meters. Based on this information both sites should be reclassified as ground moraine depressions and do not constitute areas of concern.

PUBLICATIONS

To date, this research has supported one undergraduate thesis, and five conference presentations at scientific meetings (see citations below). We anticipate all GIS products to be completed by July 2012. This research is continuing to support one other undergraduate thesis which should be finished by Spring 2013. A total of five undergraduate students and one high school student were trained in hydrology and geospatial analysis during this research project.

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GIS PRODUCTS

This research has produced the following GIS products so far:

Watersheds associated with karst features in Genesee County
Effective karst zones associated with suspicious karst features
Miscellaneous culverts and channels associated with karst features in Genesee County

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Table 1 Karst features reviewed in this study. Site-IDs and type refer to the sinkhole IDs and classification description of Richards et al (2010).

Site-ID	Location	Type	Figure in report	Effective Area (sq km)	Crop %*
1	GCC, Batavia	Glacially enhanced	3	0.024	78.1
2	GCC, Batavia	Glacially enhanced	4	0.322	50.4
3	Seven Springs Rd., Batavia	Glacially enhanced	5	0.014	48.9
9	Prentice Rd., Leroy	Glacial Moraine**	6	0.113	59.9
10	Nilesville Rd., Leroy	Glacial Moraine**	7	0.051	72.0
11	Buckley Rd., Leroy	Solution sinkhole	8	0.600	89.8
14	Galloway Rd., Batavia	Solution sinkhole	9	0.137	80.0
15	Rte 63, Batavia	Exposed bedrock	10	1.441	65.7
15a	Townline Rd., Batavia	Solution sinkhole	11	0.094	74.8
17	State Rd, Batavia	Glacially enhanced	12		
18	Saile Drive, Batavia	Glacially enhanced	13		
19	Fargo Rd., Stafford	Exposed bedrock	14	0.319	49.0
20	RR line, Caledonia	Exposed Bedrock	15	0.312	51.2
21	RR line, Caledonia	Solution sinkhole	16	0.026	81.6
23	Rte 5, Leroy	Solution sinkhole	17	0.012	46.6
27	Rte 5, Caledonia	patterned ground sinkhole	18	0.094	49.8
31	Gulf Rd., Leroy	Solution sinkhole	19	2.487	63.4
33	Rte 5, Caledonia	Patterned ground sinkhole	20		
34	Quinlan Rd., Leroy	Solution sinkhole	21	0.013	64.0
39	Middle Rd., Caledonia	Exposed Bedrock	22		
42	Pratt Rd., Batavia	Solution sinkhole	23	0.005	76.8
45	Main Rd., Batavia	Glacially enhanced	24	0.015	41.2
45a	Main Rd. Batavia	Glacially enhanced	25	0.005	31.5
53	Alleghany Rd., Pembroke	Glacially enhanced	26	0.039	61.8
54	Read Rd., Batavia	Glacially enhanced	27	0.009	40.6
55	Callan Rd., Limerock	Patterned ground sinkhole	28	0.087	80.4
56	Rte 5, Limerock	Patterned ground sinkhole	29	0.915	74.4
58	Britt Rd., Leroy	Glacially enhanced	30	0.352	77.8
62	Circular Hill Rd, Leroy	Exposed Bedrock Feature	31	0.102	12.7

* Cropland determined within the true catchment associated with the effective area of the karst feature.

** Originally classified as a glacially enhanced sinkhole.

Table 2 Sinkholes ranked by Watershed / Effective area indices.

Site No	True watershed area (sq km)	Watershed / Effective area index (True)	(JD)*	(PCSA)**	Comments
23	7.46	621.7	469.2	977.0	Karst-related flooding
54	2.18	242.1	243.5	195.4	
34	2.44	192.1	106.6	254.2	Karst-related flooding
21	2.90	111.3	107.9	247.9	
45a	0.34	64.7	69.7	31.6	
42	0.23	45.1	47.2	61.7	
3	0.50	36.3	81.3	47.4	Clarendon-Linden fault
53	1.26	32.3	34.9	34.9	
55	1.88	21.6	21.3	55.3	
15a	1.69	18.1	25.8	18.1	
1	0.40	16.8	14.3	28.1	
31	35.91	14.4	16.0	21.7	Karst-related flooding
56	9.20	10.1	9.9	20.7	Karst-related flooding
10	0.45	8.9	4.3	7.6	
45	0.13	8.8	36.9	17.3	
19	2.05	6.4	8.2	7.0	
15	7.57	5.3	9.5	5.1	2007 Well contamination event
2	1.40	4.3	4.8	7.8	
9	0.44	3.9	2.9	7.8	
58	0.97	2.8	3.9	8.2	Karst-related flooding
27	0.19	2.1	5.1	21.2	
11	1.22	2.0	2.2	3.2	
20	0.56	1.8	0.5	5.3	
14	0.20	1.4	1.5	2.4	
61	0.10	1.0	0.6	2.2	

* Watershed delineated using the Jensen and Domingue algorithm.

** Watershed delineated using the PCSA algorithm.

Fig. 1a (top) *Portion of study area, showing sinkholes mapped by Richards et al (2010).* ***Fig. 1b (left)*** *a "patterned ground" sinkhole.* ***Fig 1c (right)*** *inset photograph of road berm that blocks the drainage into a karst feature. These features, which are visible with LIDAR data, need to be accounted for when the delineating catchments of karst features.*

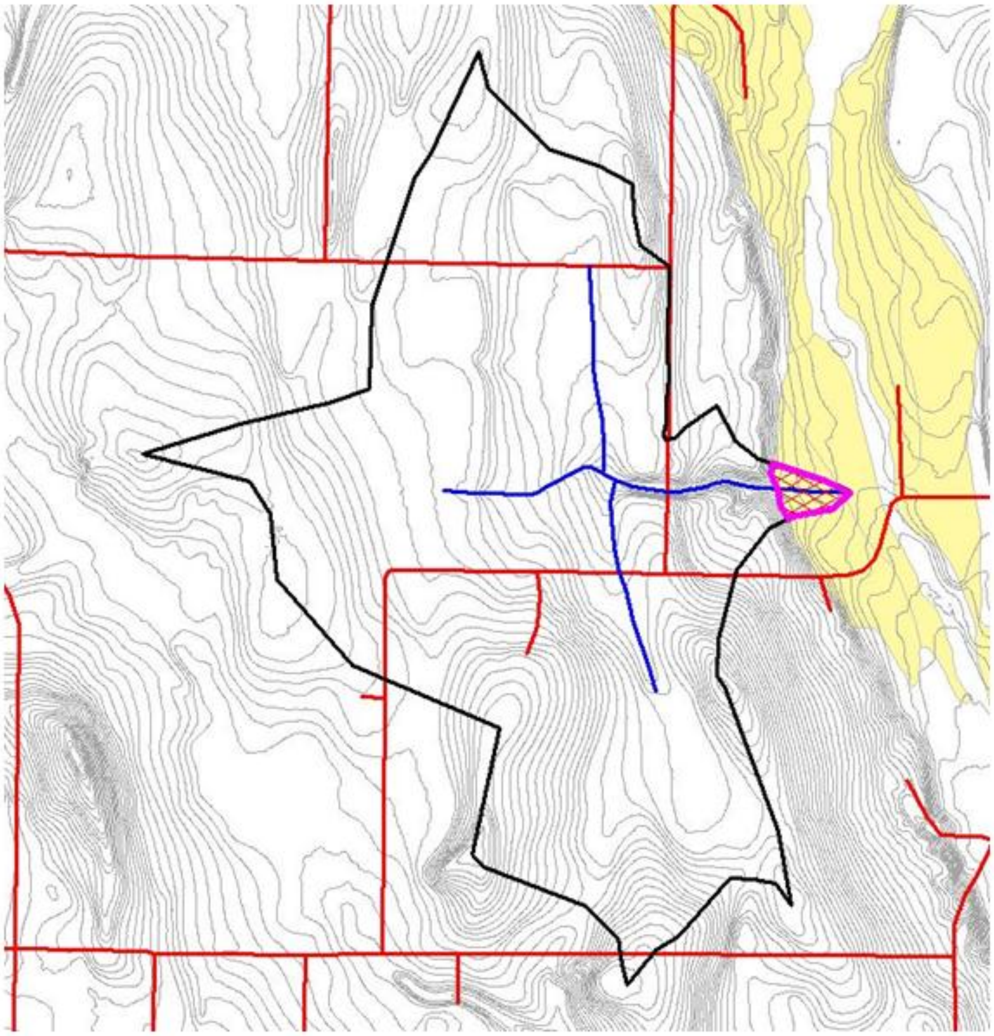

Fig. 2 *Schematic of the concept of the Catchment / Effective area ratio. The black line denotes the catchment associated with the effective zone (purple stipple). This zone is associated with sinkhole site which is located on a fracture trace covered by shallow soils (pale yellow fill). As the area of the watershed becomes larger than the effective zone, the greater the flux of nutrients can recharge into the water table in the vicinity of the effective zone. The smallest Catchment / Effective area ratio possible is 1, representing the condition where 100% of the catchment is covered by shallow soil. In this case the effective area and the watershed area are the same. SWAT is being used to estimate the flux of nutrients into the effective zone of the karst site. Flux per unit effective area can then be used to rank the sites from most susceptible to groundwater pollution to least susceptible.*

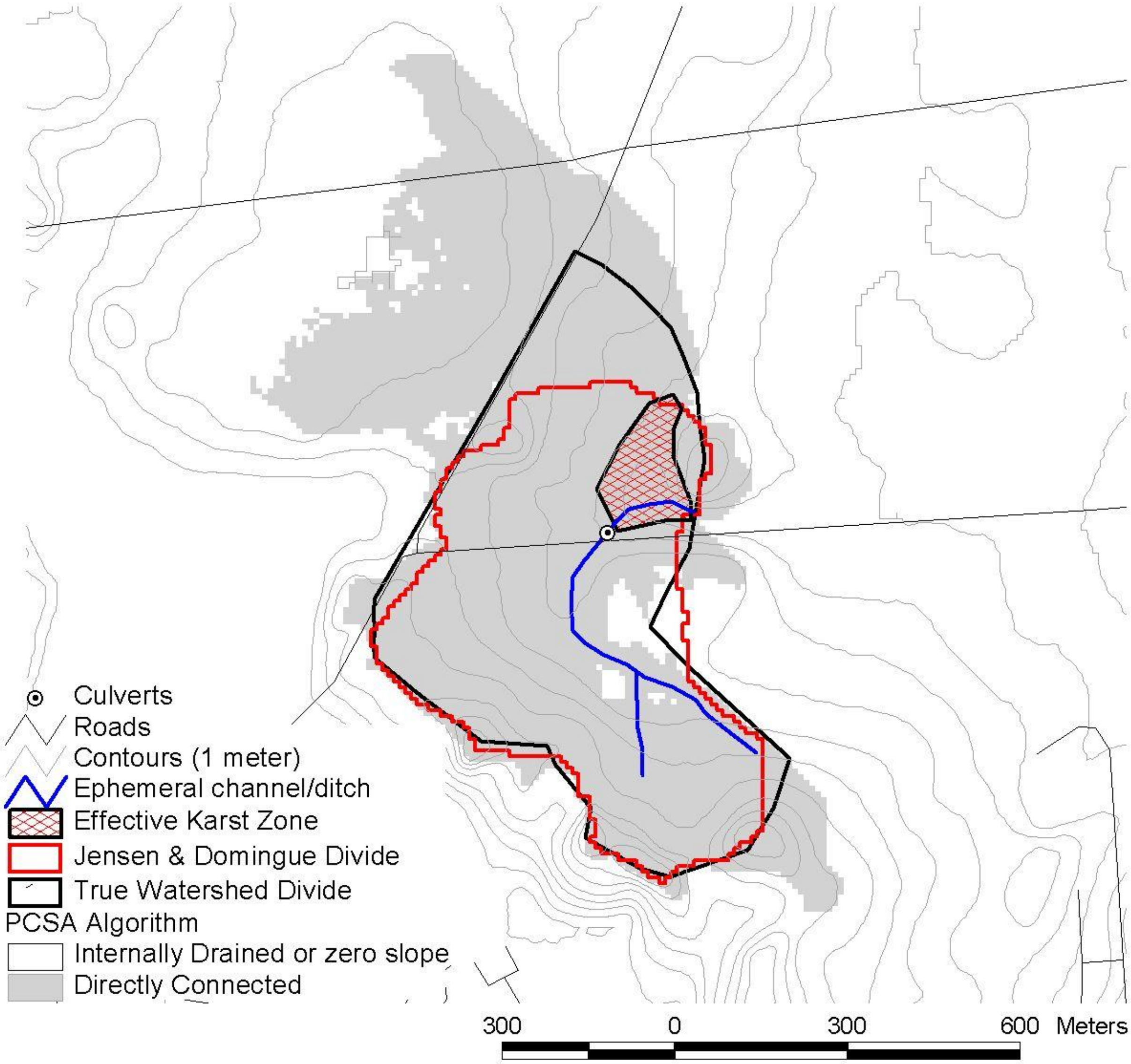

Figure 3 Site 1; a glacially enhanced sinkhole.

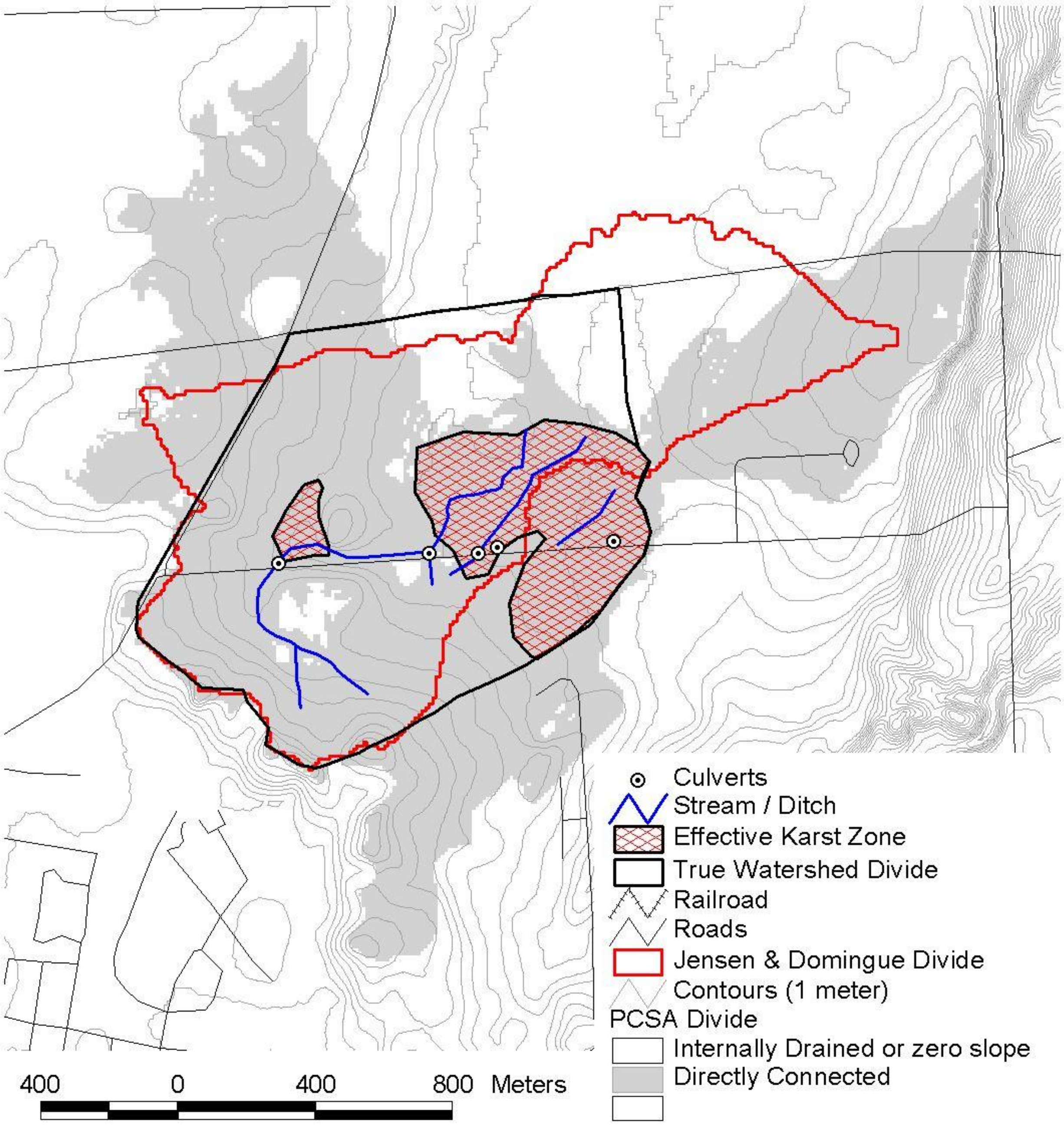

Figure 4 Site 2; a glacially enhanced sinkhole.

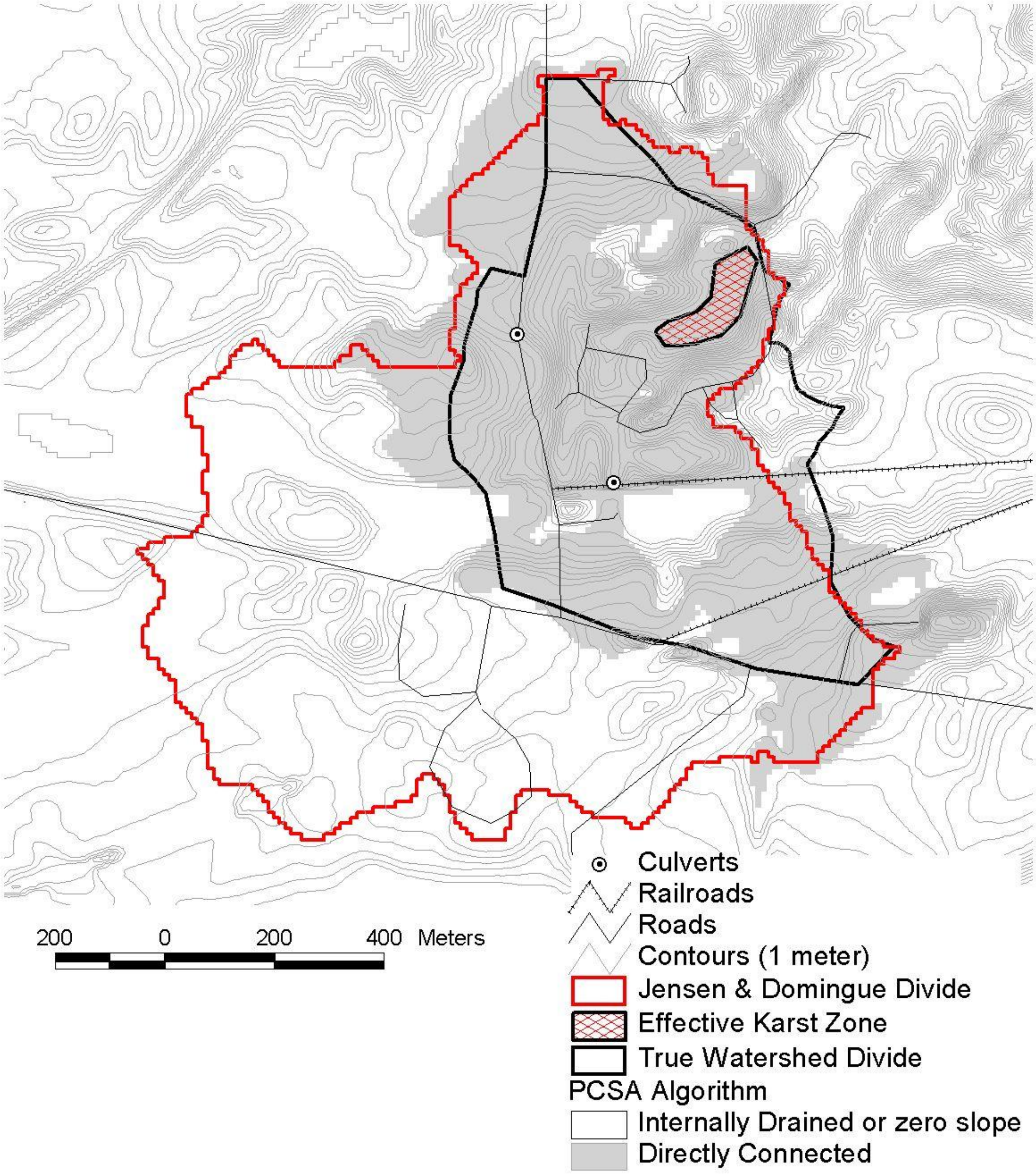

Figure 5 Site 3; Seven Springs sinkhole. A glacially enhanced sinkhole located on the Clarenden – Linden Fault system

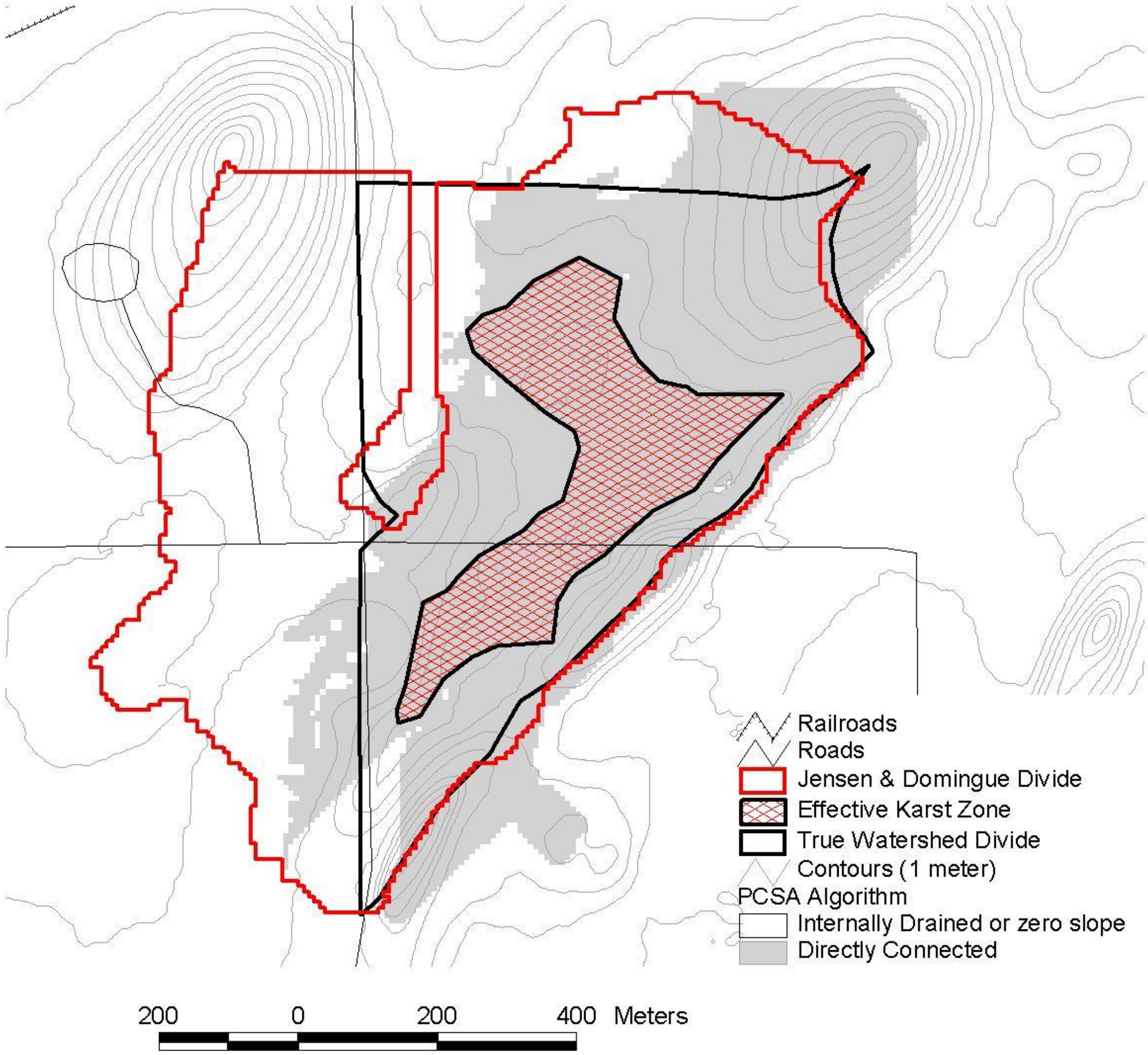

Figure 6 Site 9; originally classified as a glacially enhanced sinkhole, this sinkhole has been reclassified as a glacial feature because of the absence of bedrock and thick overburden in the site.

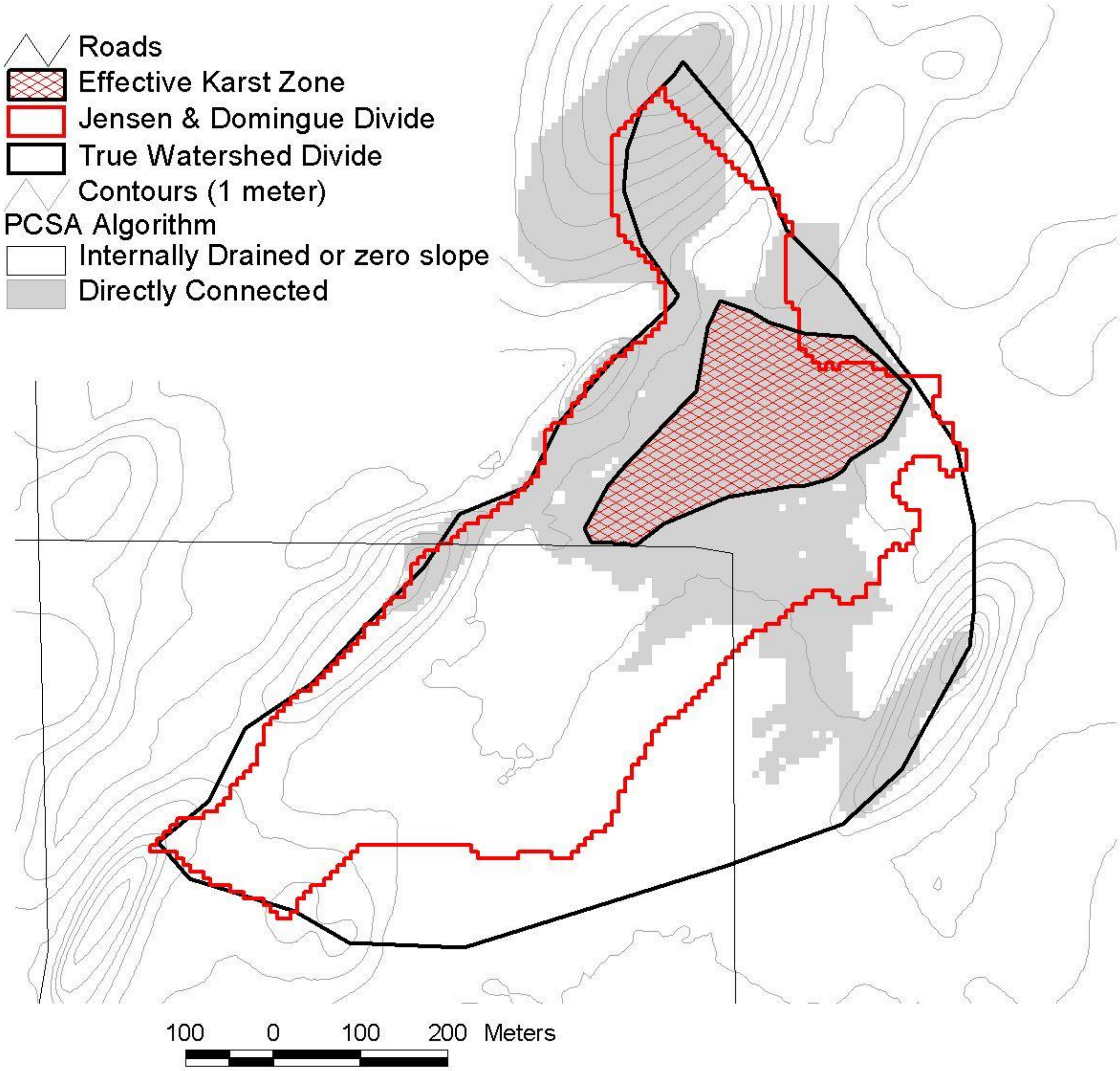

Figure 7 Site 10; originally classified as a glacially enhanced sinkhole, this sinkhole has been reclassified as a glacial feature because of the absence of bedrock and thick overburden in the site.

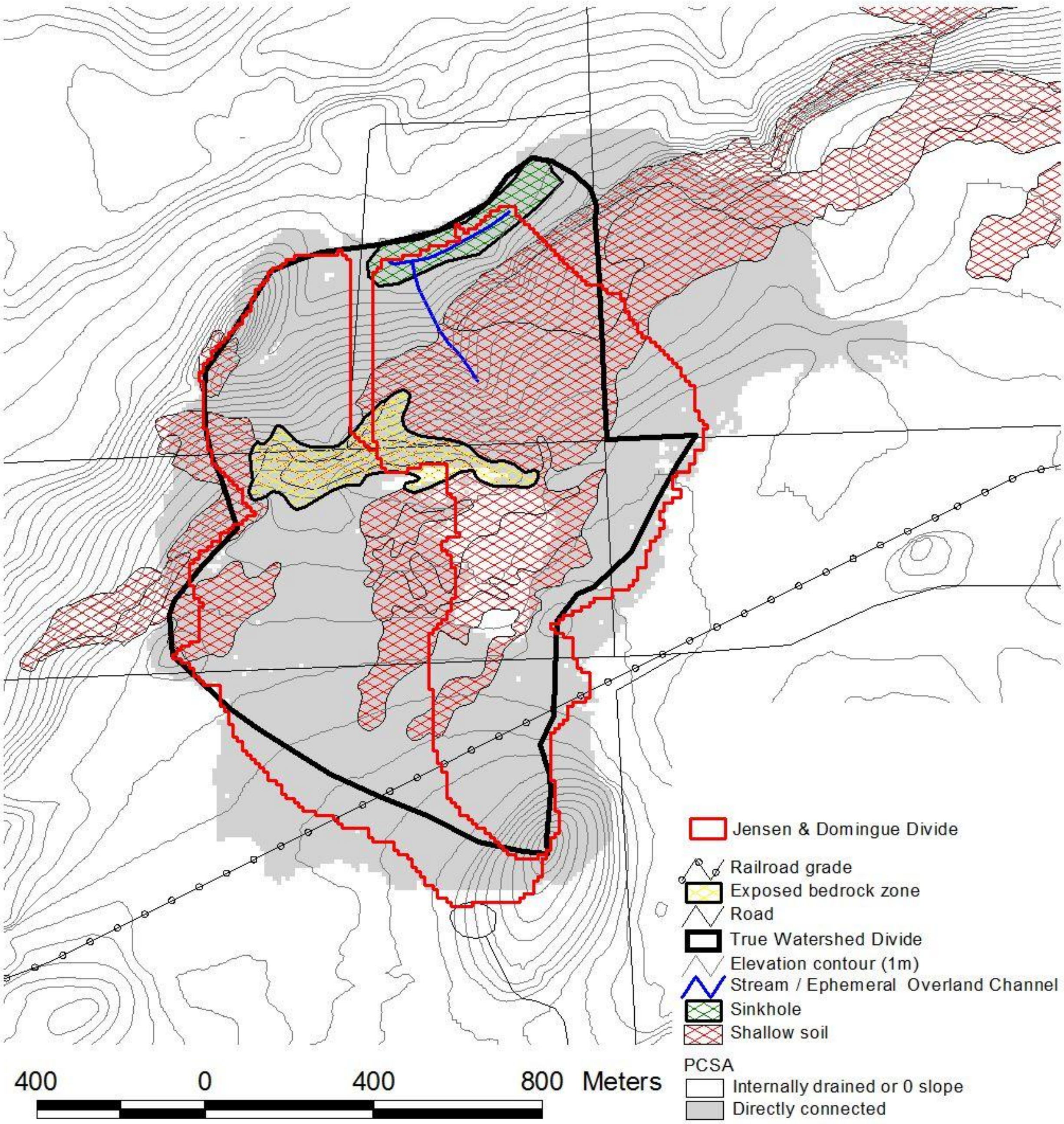

Figure 8 Site 11; the Buckley Rd. sinkhole system. Contains fractured bedrock and a solution sinkhole located on a fracture trace.

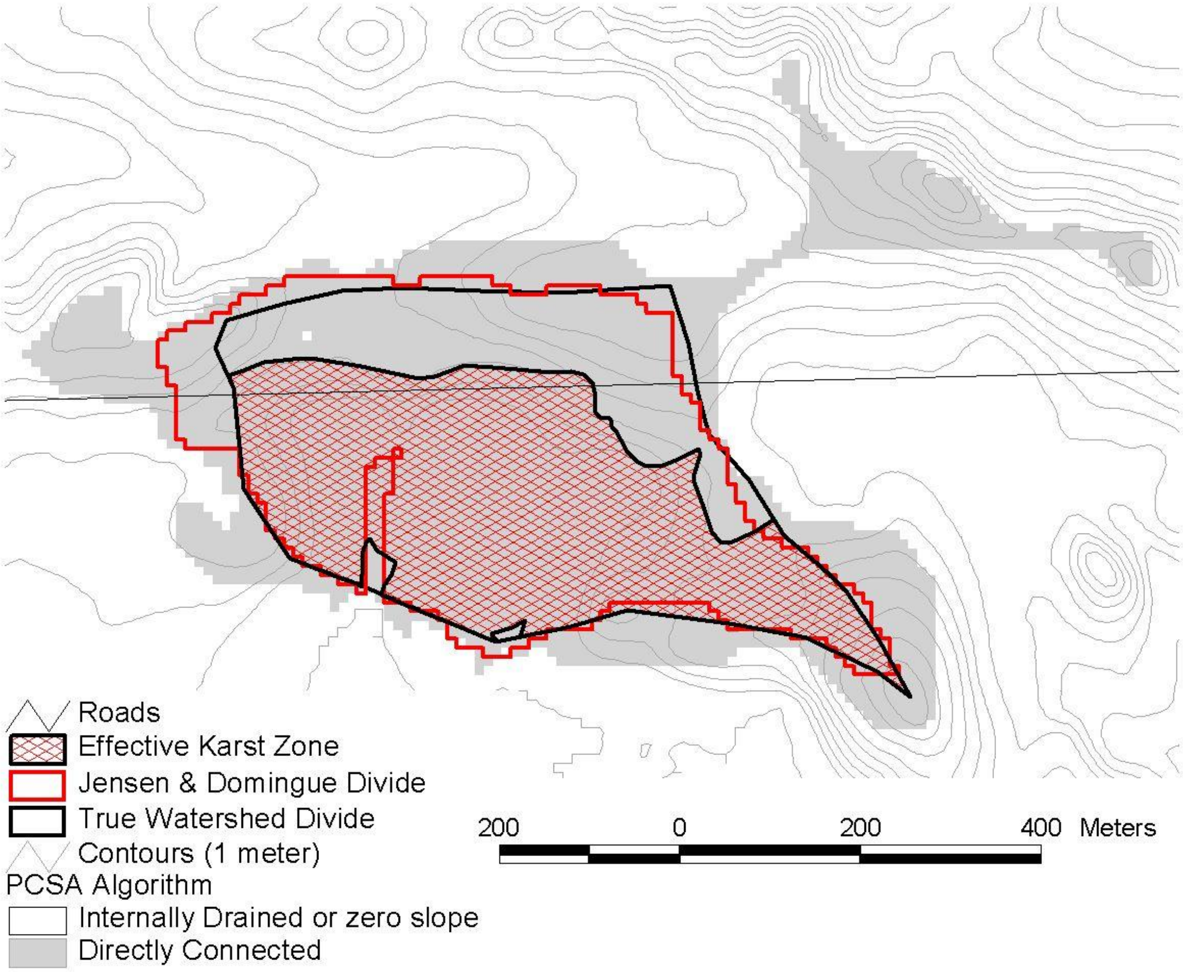

Figure 9 Site 14; a glacially enhanced sinkhole.

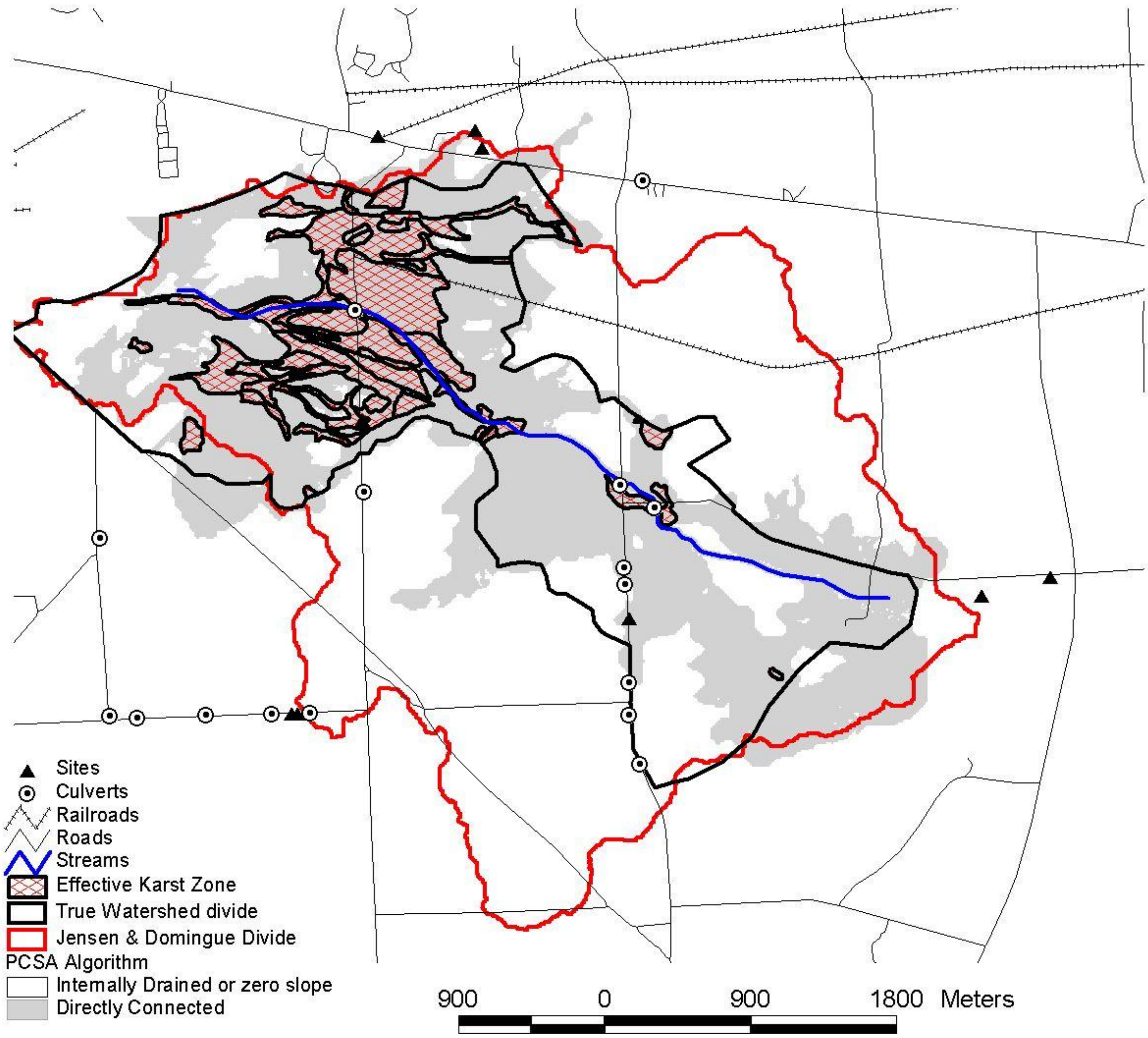

Figure 10 Site 15; a complex thinly soiled karst system composed of multiple thinly-soiled karst features. Site of the 2007 well contamination event.

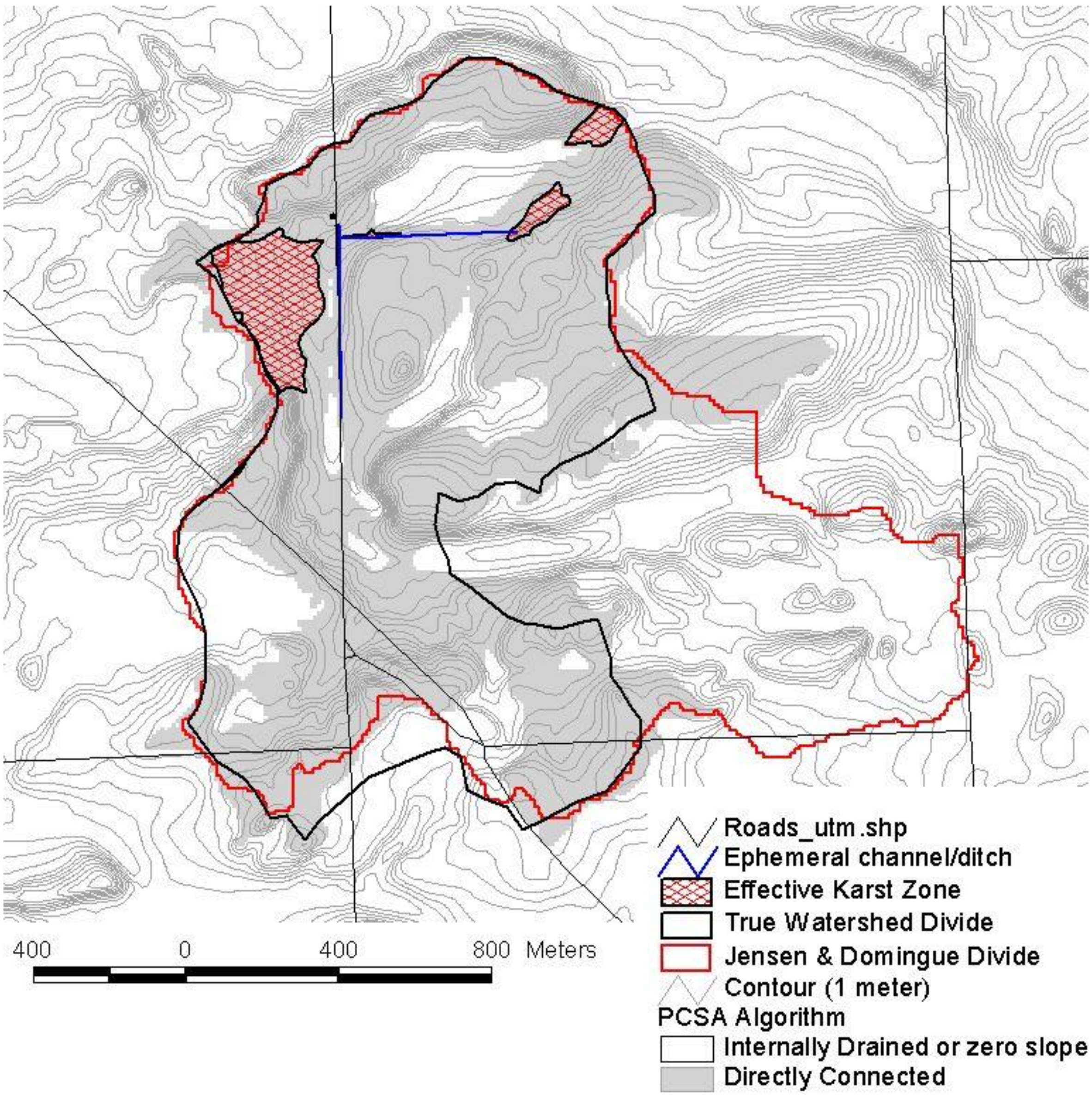

Figure 11 Site 15a; a solution sinkhole. Drainage in this feature is augmented by a drainage ditch along Townline Rd.

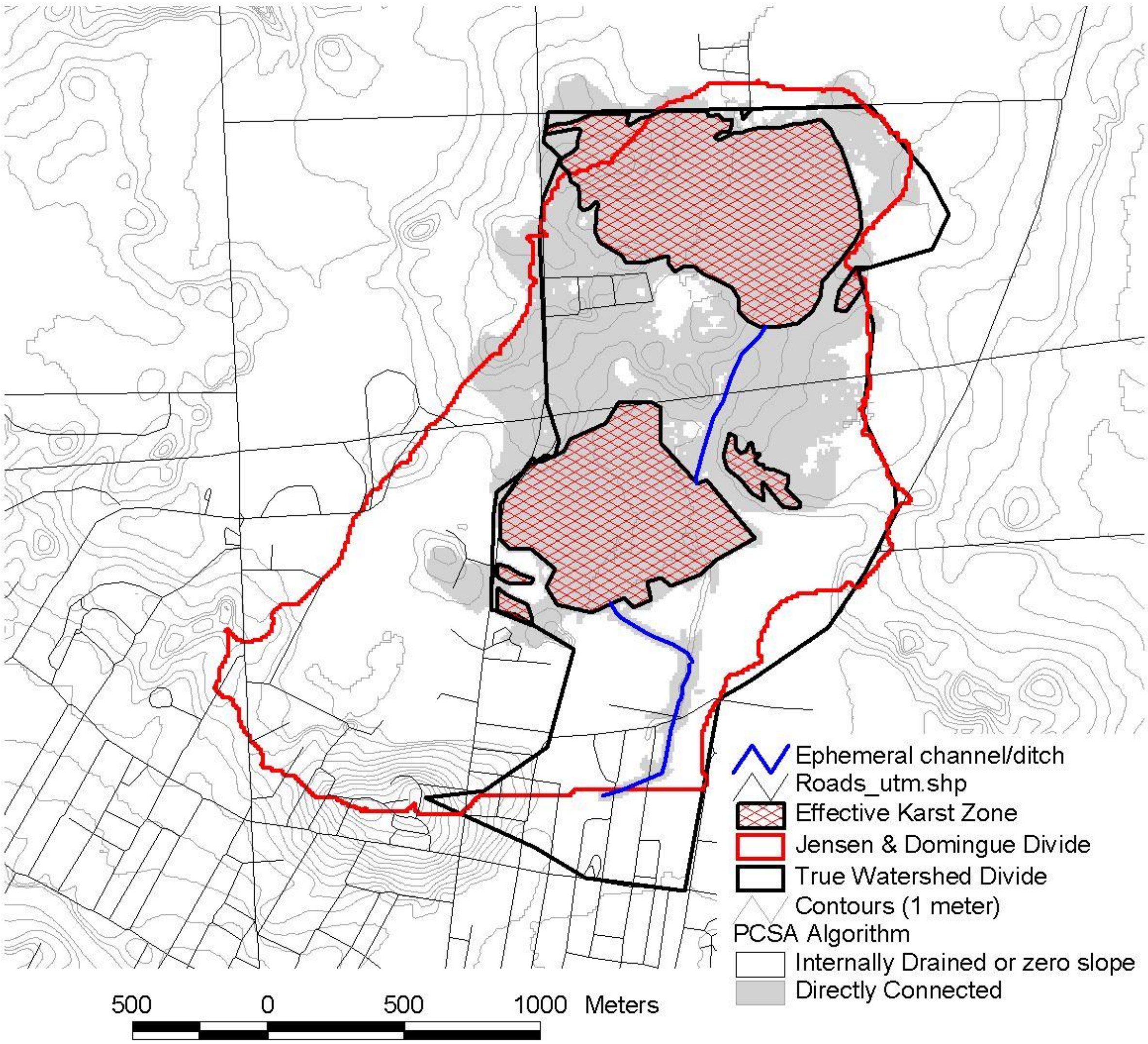

Figure 12 Site 17; A glacially enhanced sinkhole system. Site of the 2004 Bensen heights well contamination event.

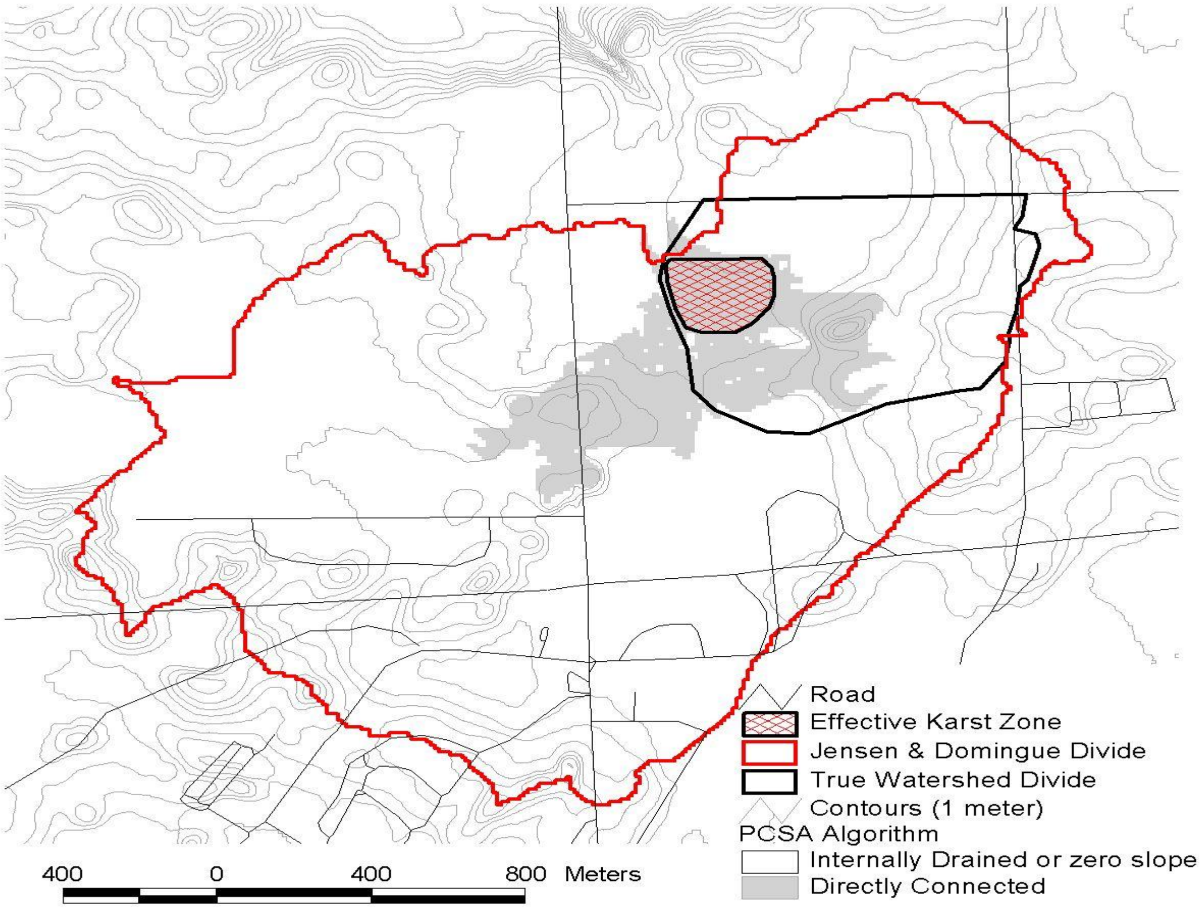

Figure 13 Site 18; a glacially enhanced sinkhole system. Site of an odd construction flooding event.

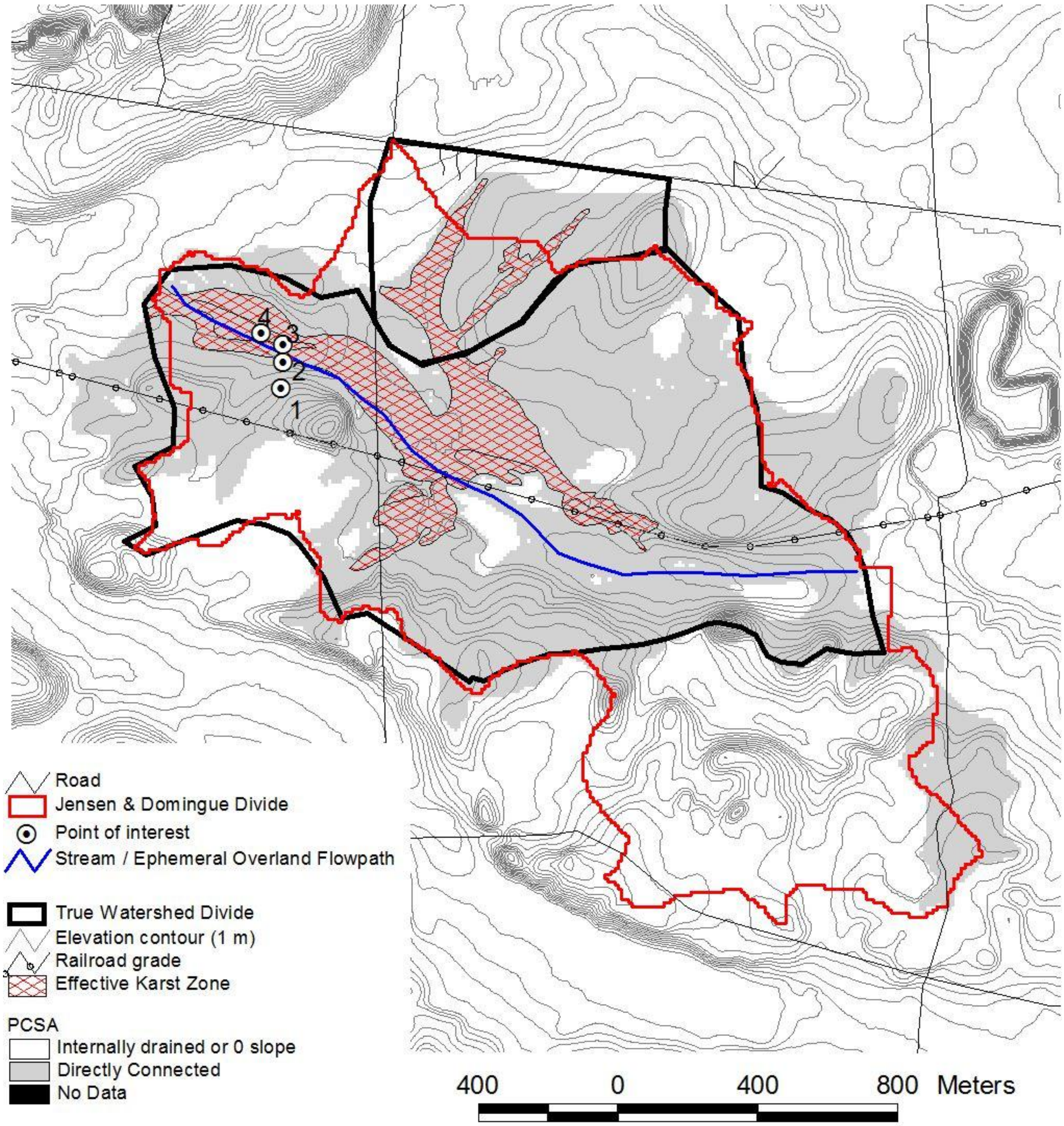

Figure 14 Sites 19 and 19a; The Fargo rd sinkhole system. Solution sinkholes located on a fracture trace.

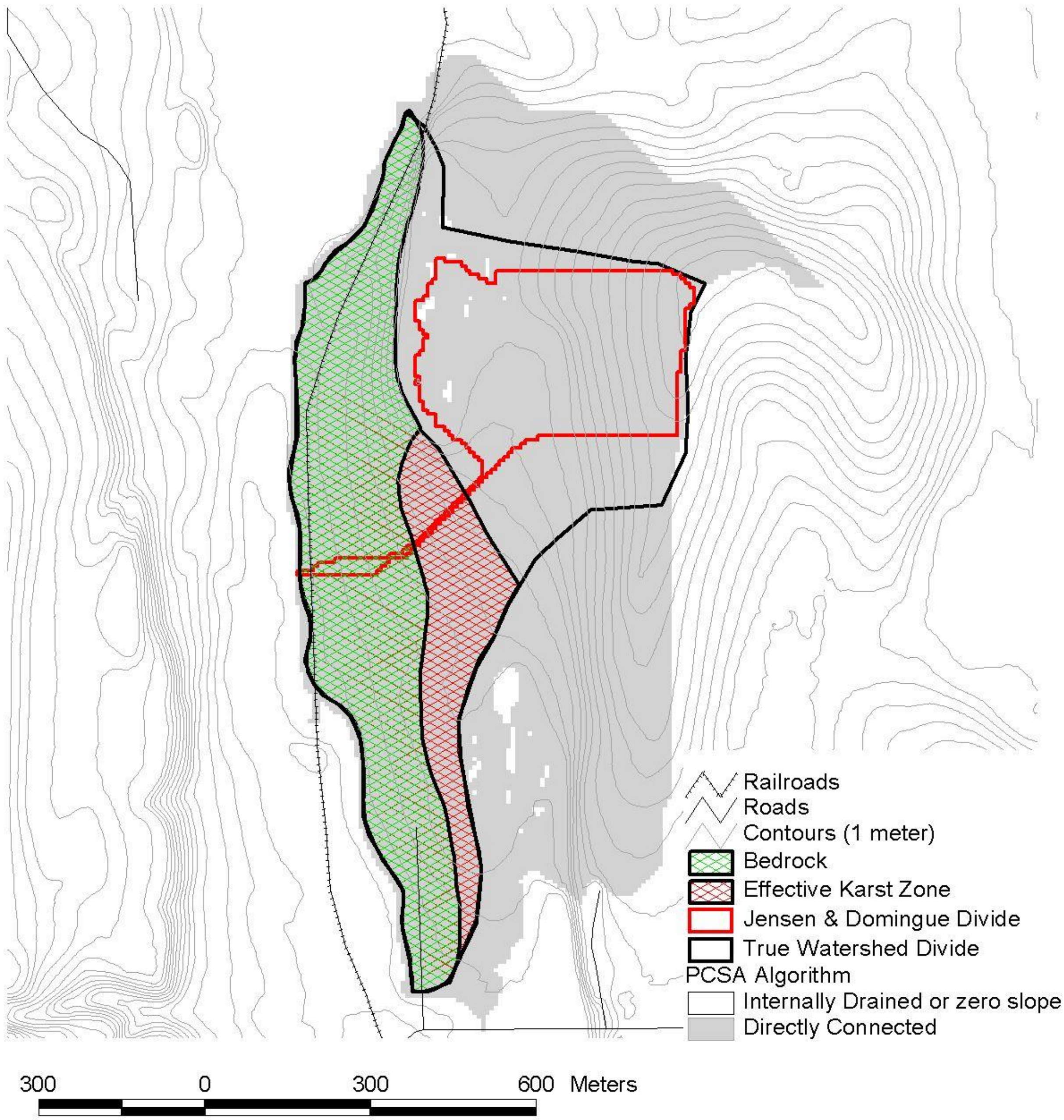

Figure 15 Site 20; a fractured bedrock zone located on the side of a fracture trace.

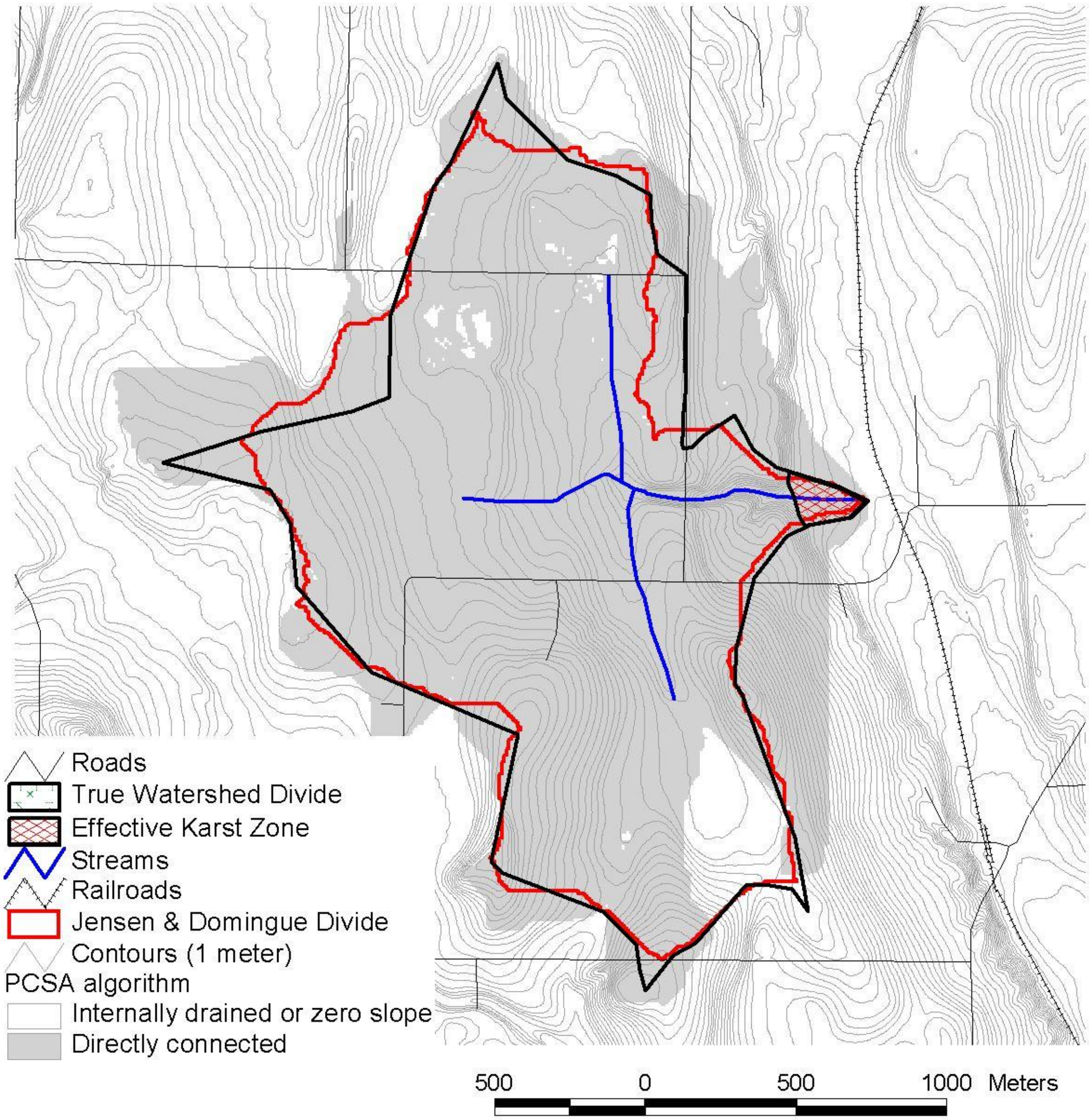

Figure 16 Site 21; a solution sinkhole located on a fracture trace.

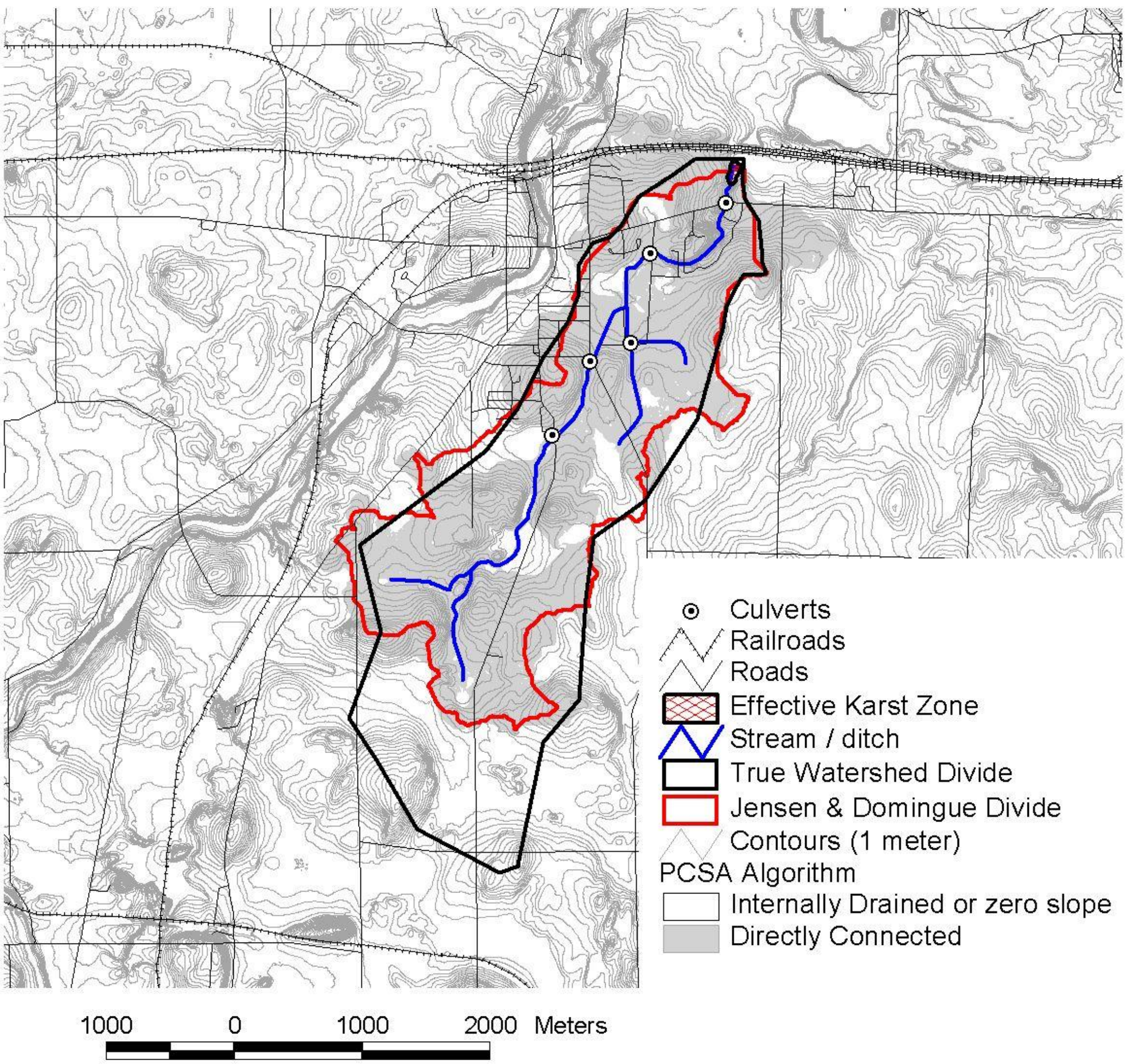

Figure 17 Site 23; the "Golf course" sinkhole. A solution sinkhole located at Rte 5 just east of Leroy.

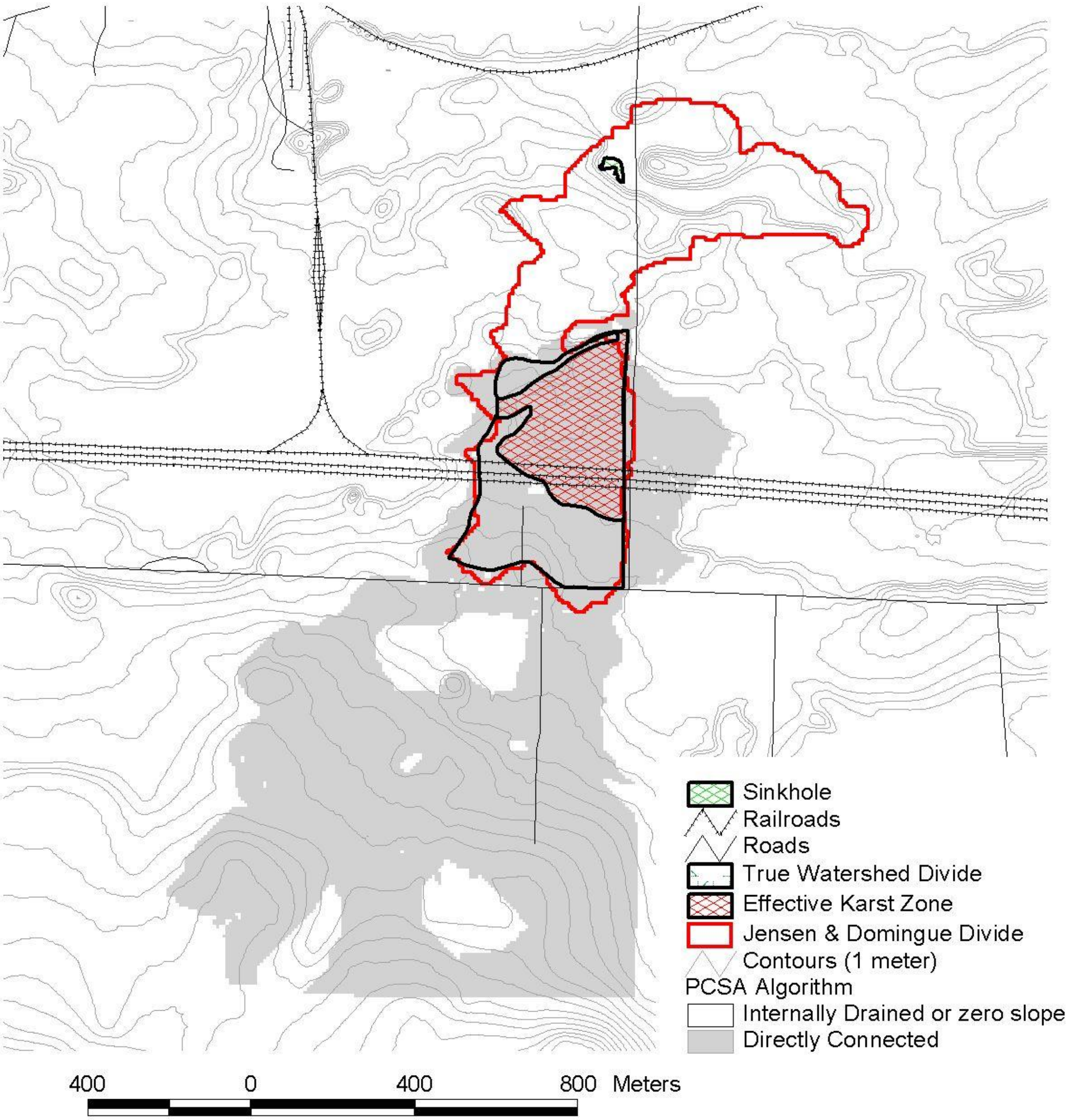

Figure 18 Site 27; A patterned ground sinkhole.

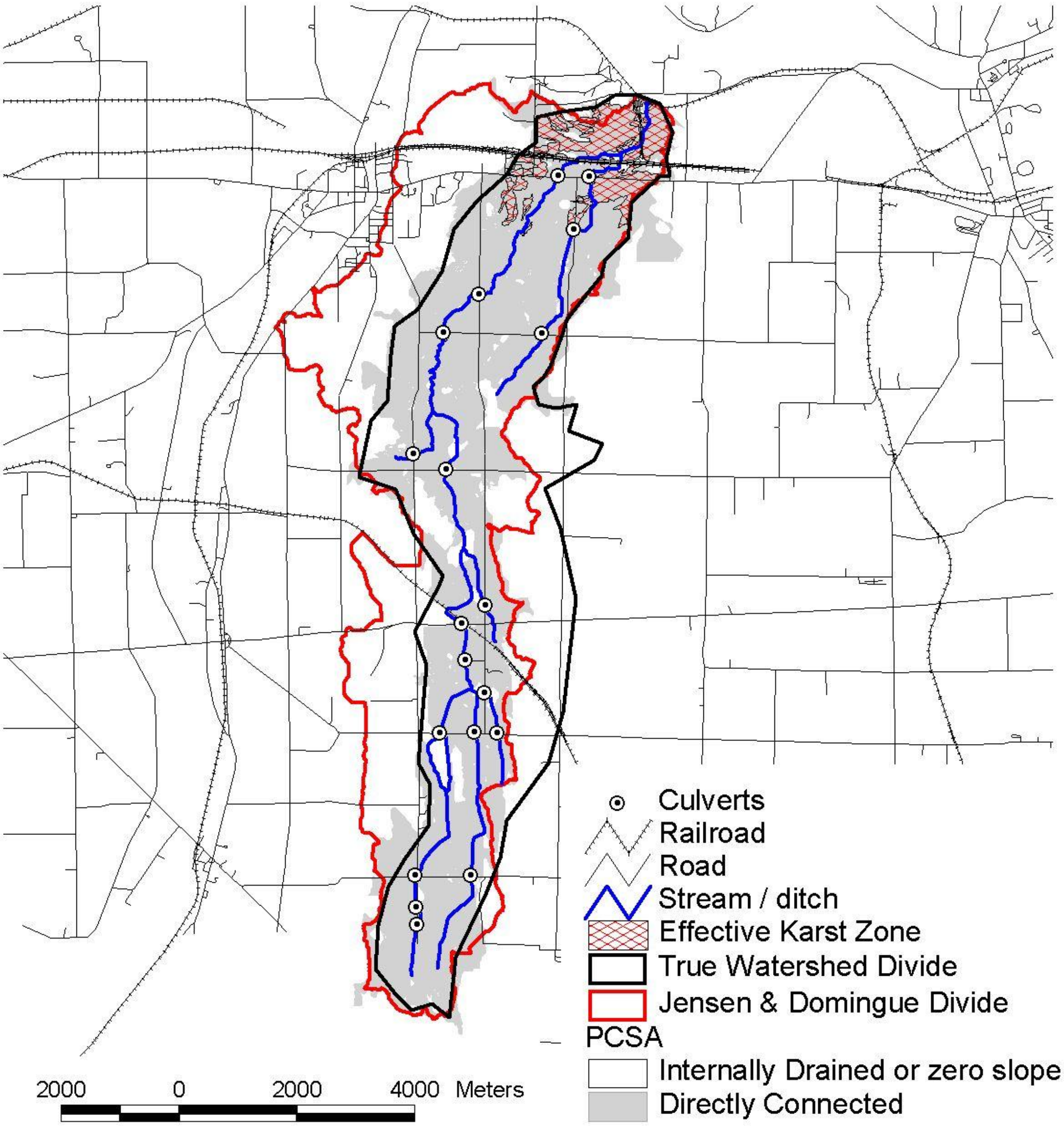

Figure 19 Site 31; the Mud Creek Sinkhole system. A solution sinkhole intercepting one of the larger tributaries for Oatka Creek.

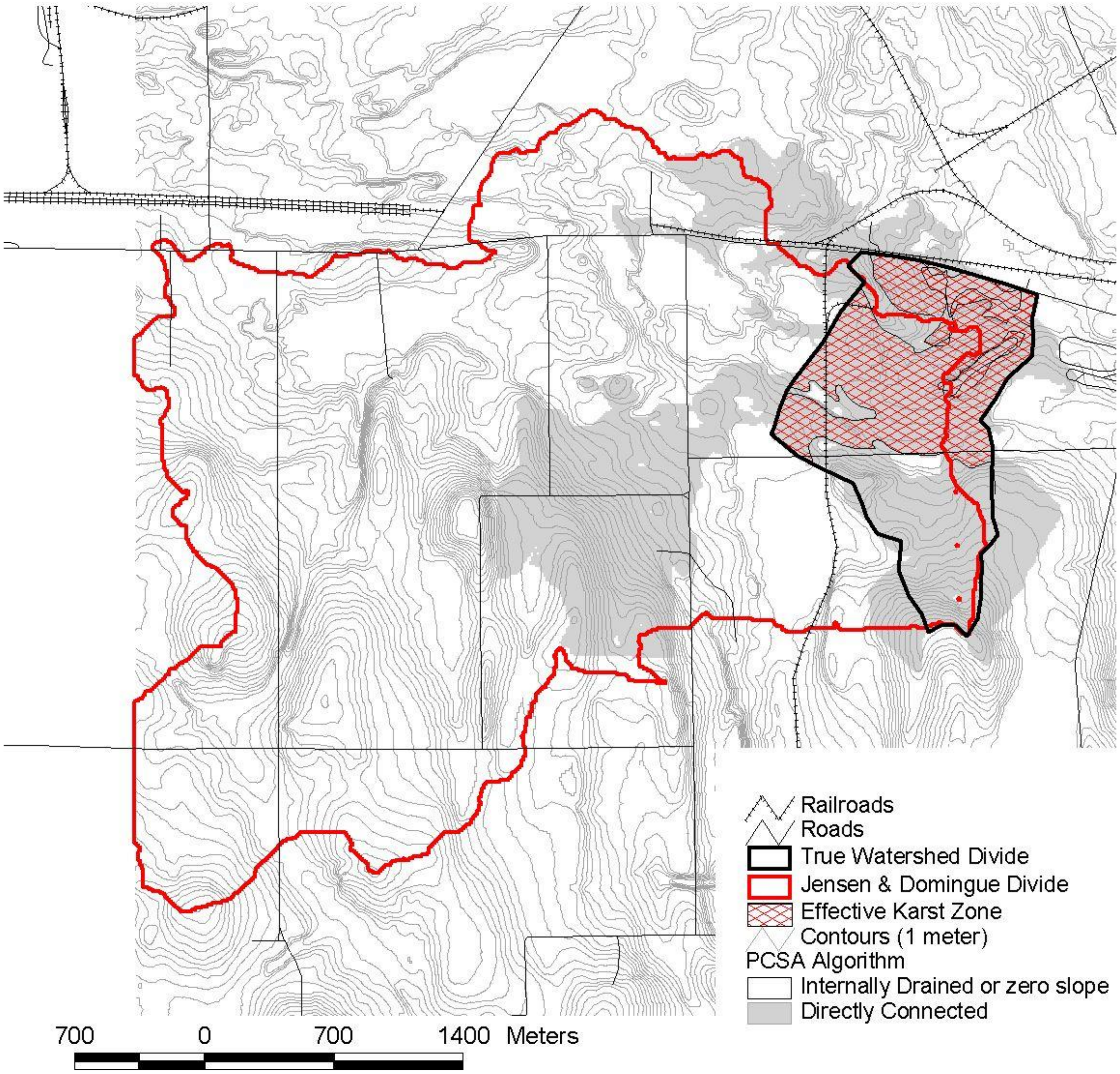

Figure 20 Site 33; a patterned ground sinkhole.

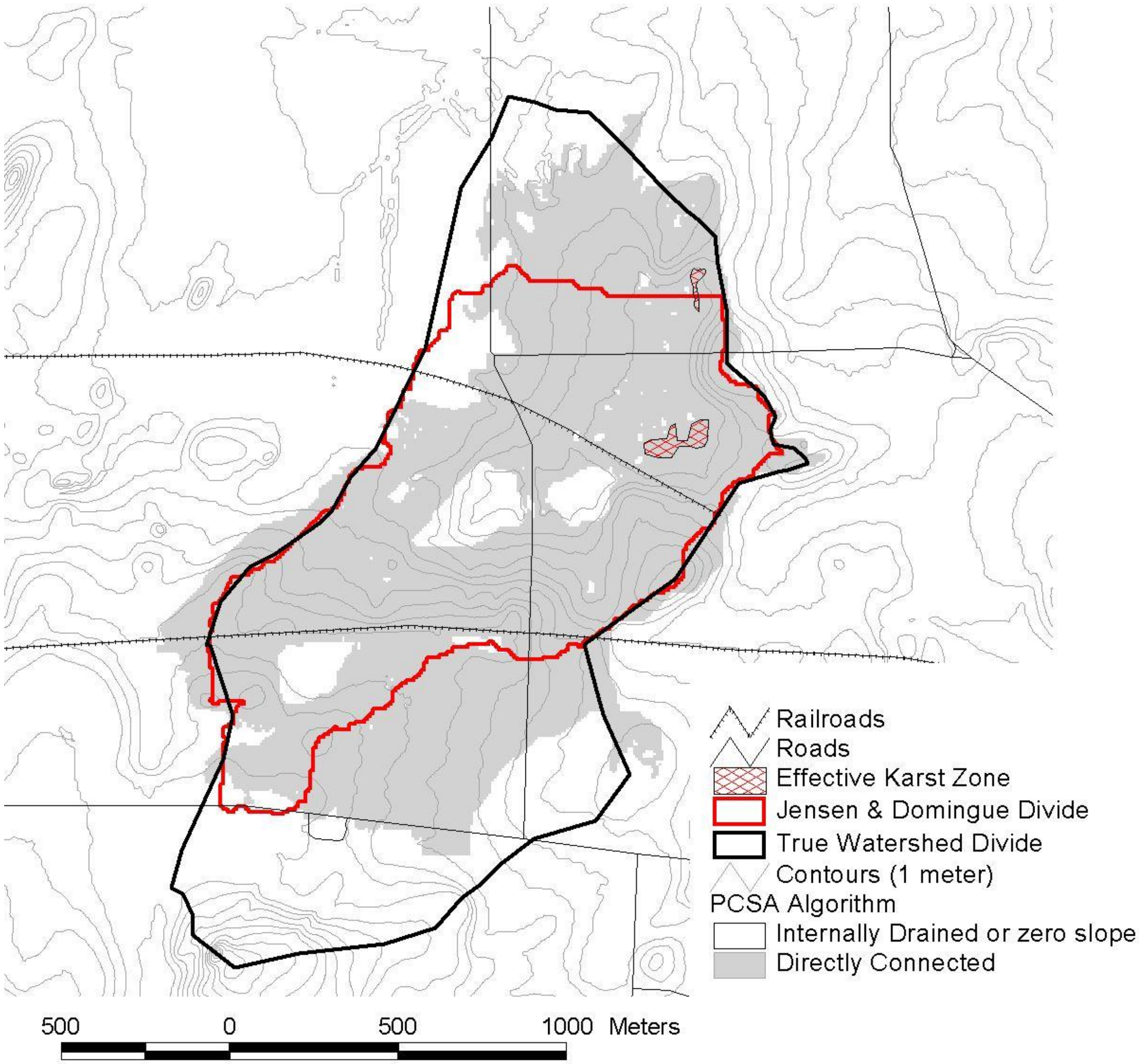

Figure 21 Site 34; the Quinlan Rd sinkhole system.

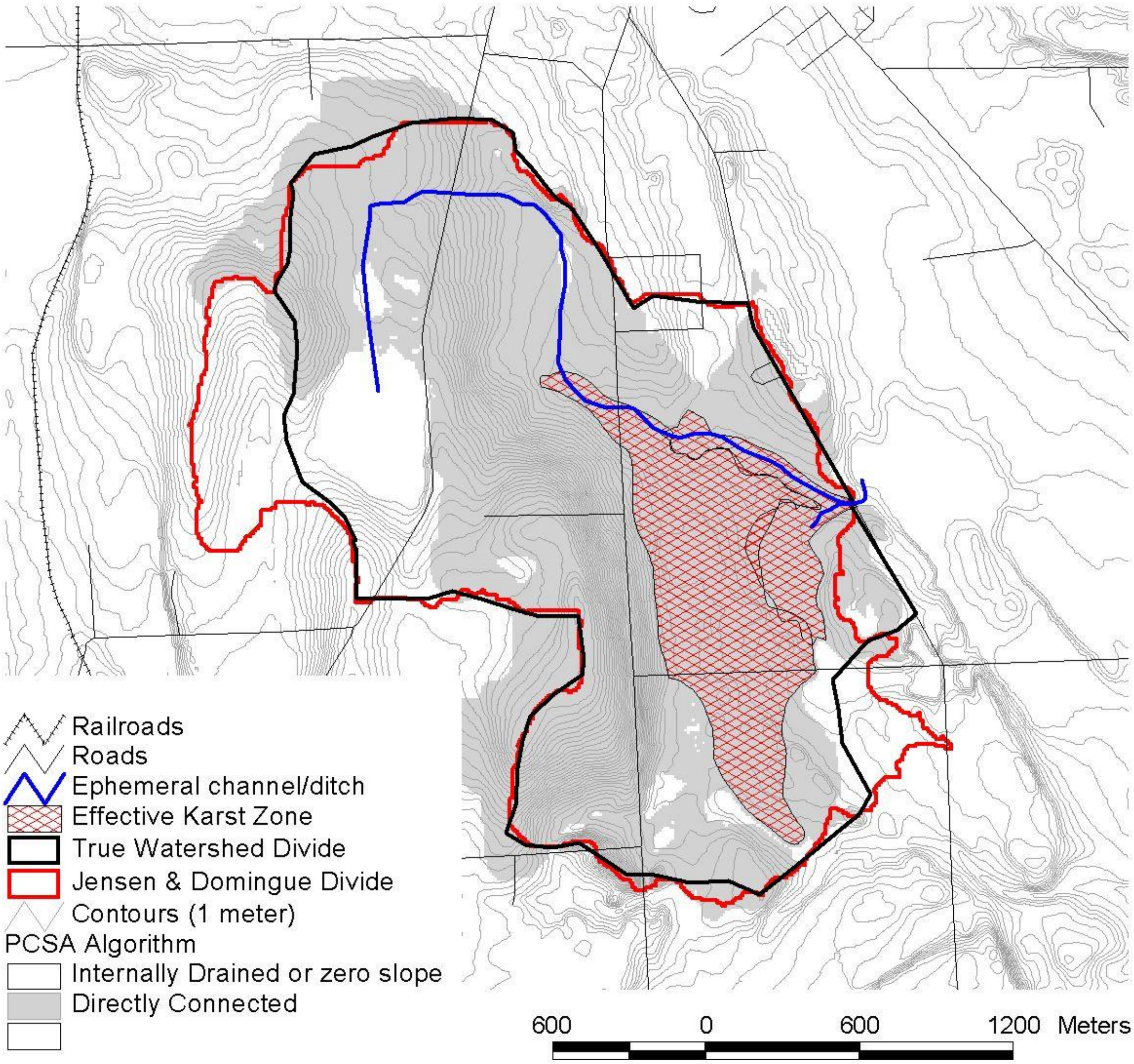

Figure 22 Site 39; a glacially-enhanced sinkhole system. Note, still needs to be field checked.

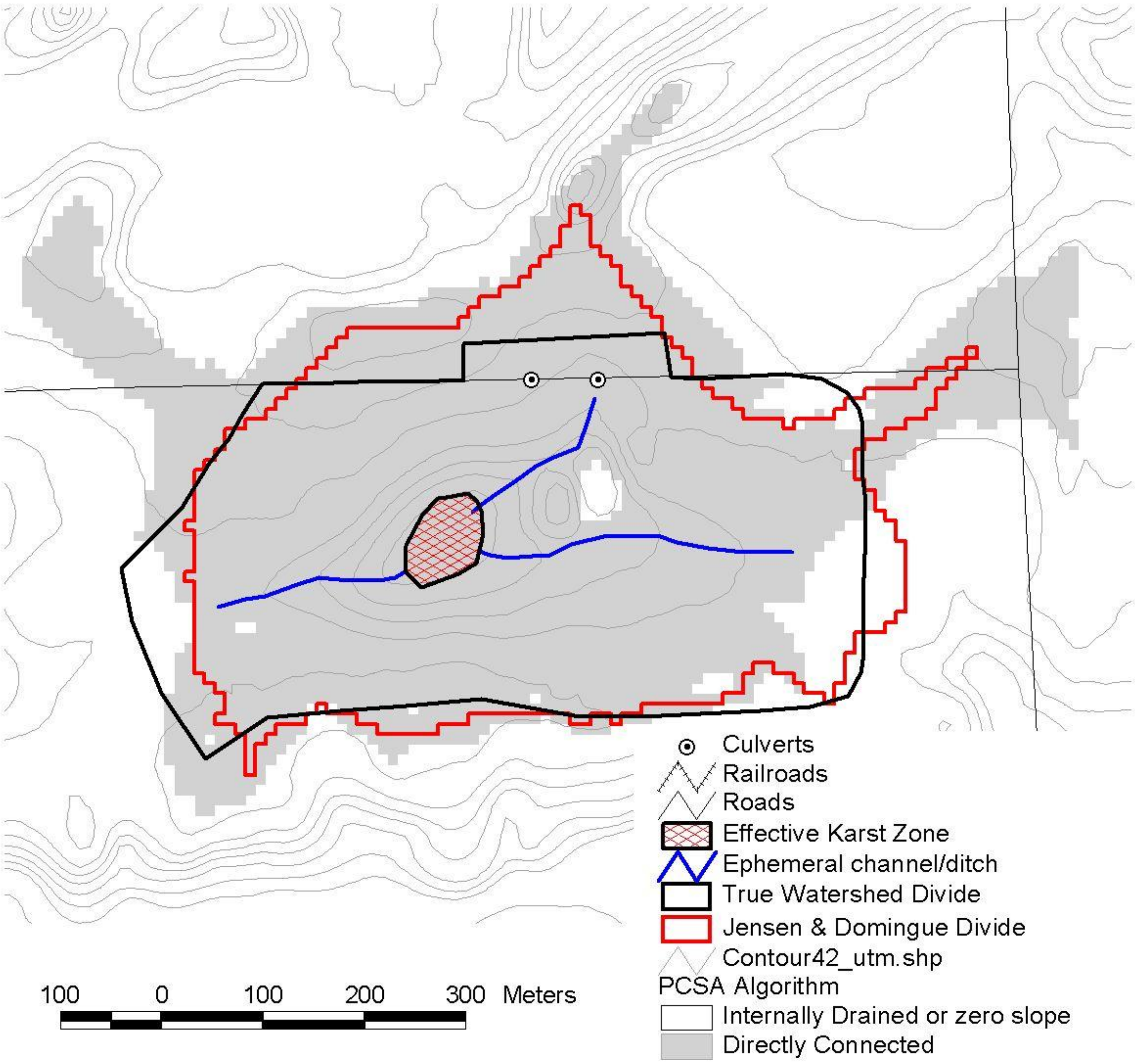

Figure 23 Site 42; a solution sinkhole.

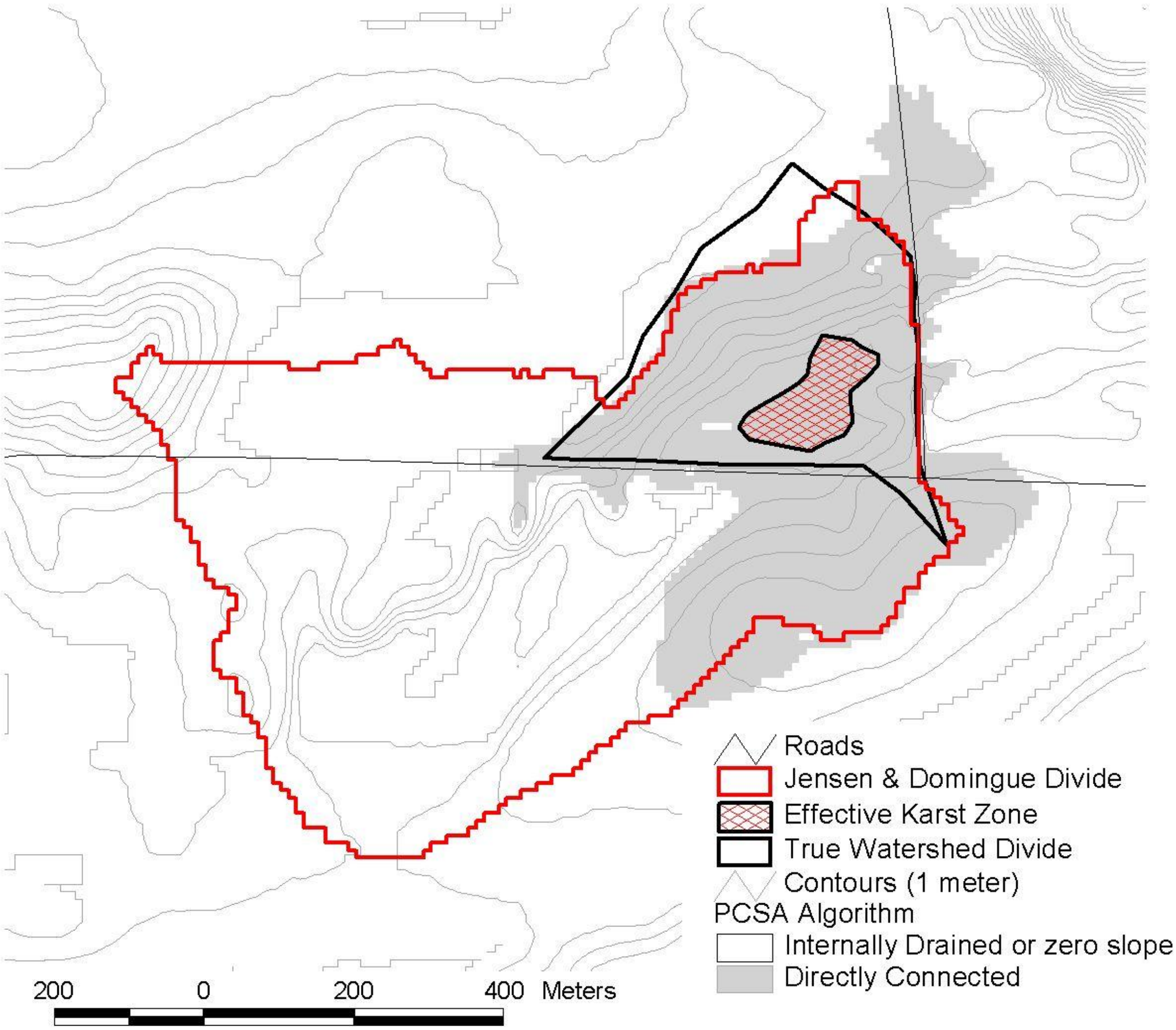

Figure 24 Site 45; a glacially-enhanced sinkhole.

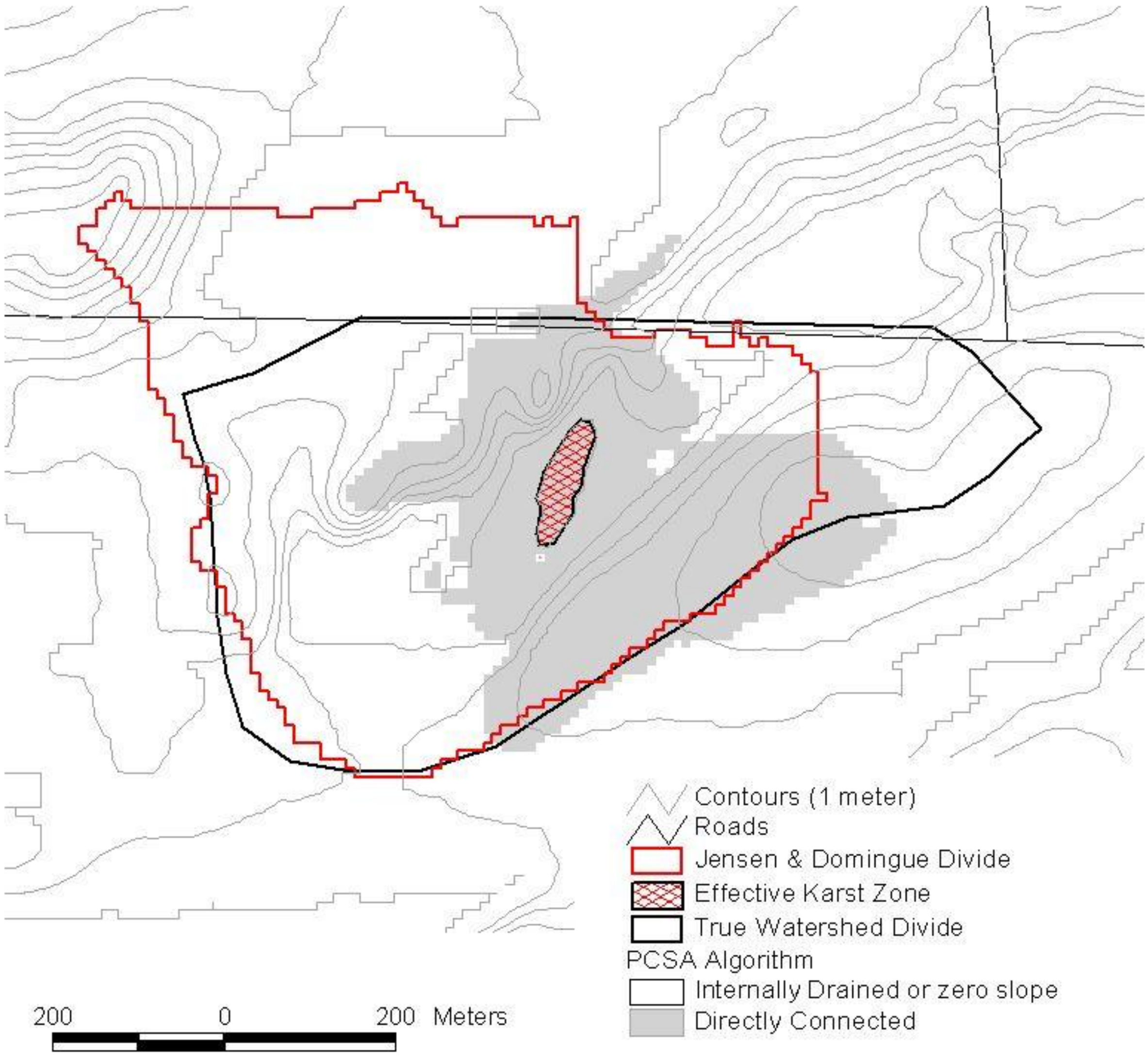

Figure 25 Site 45a; a glacially-enhanced sinkhole.

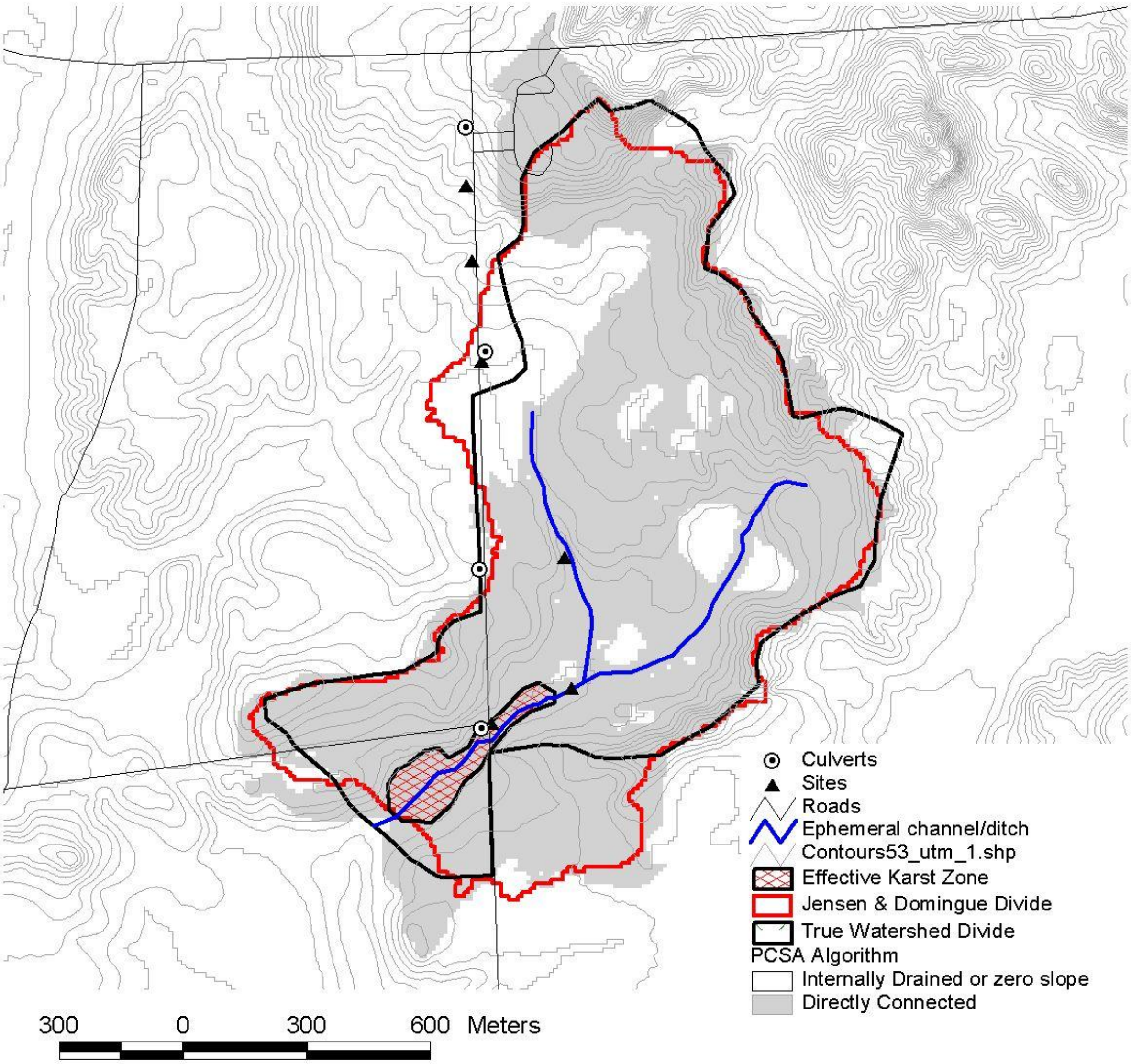

Figure 26 Site 53; a glacially enhanced sinkhole system.

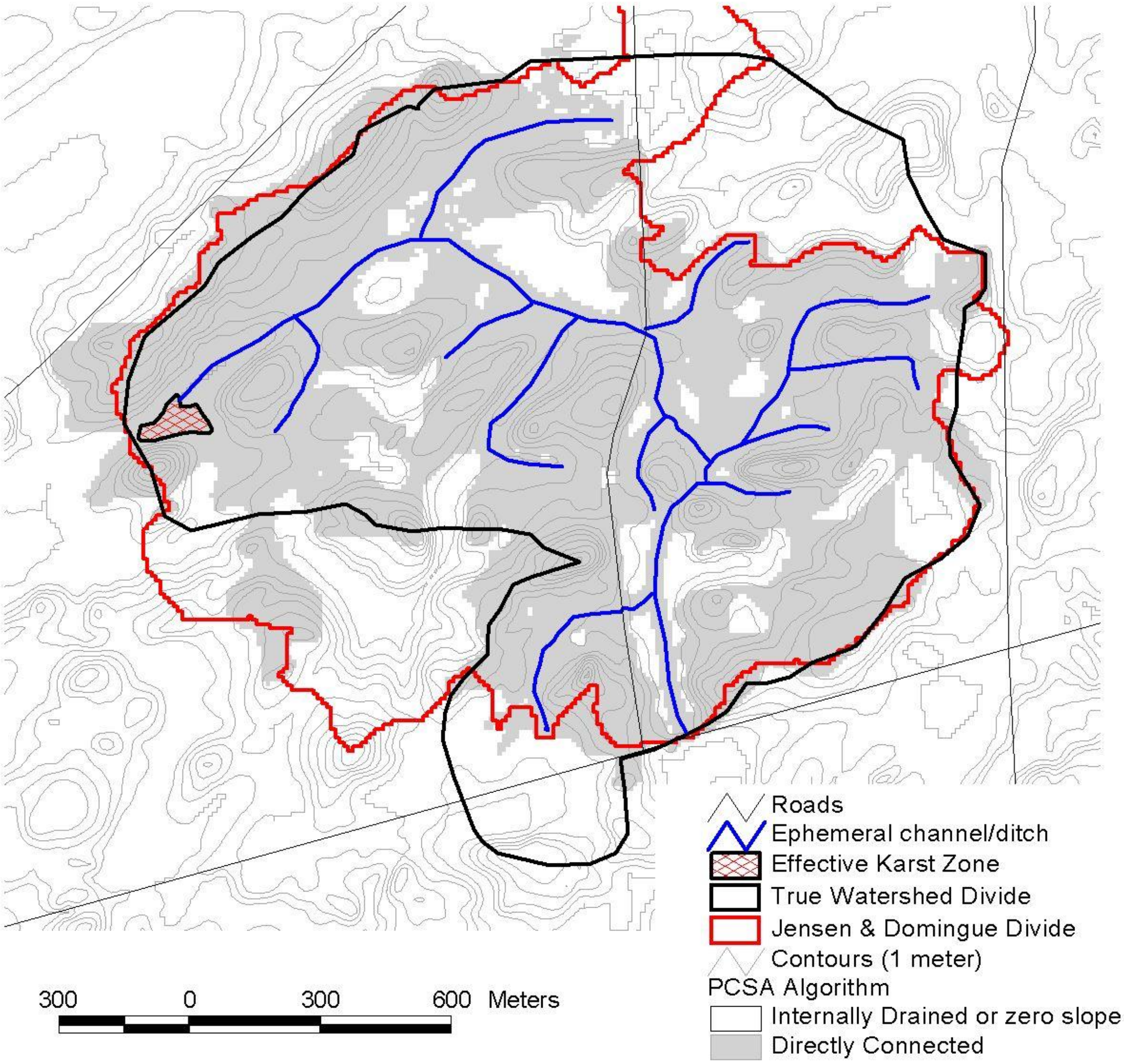

Figure 27 Site 54, a patterned ground sinkhole.

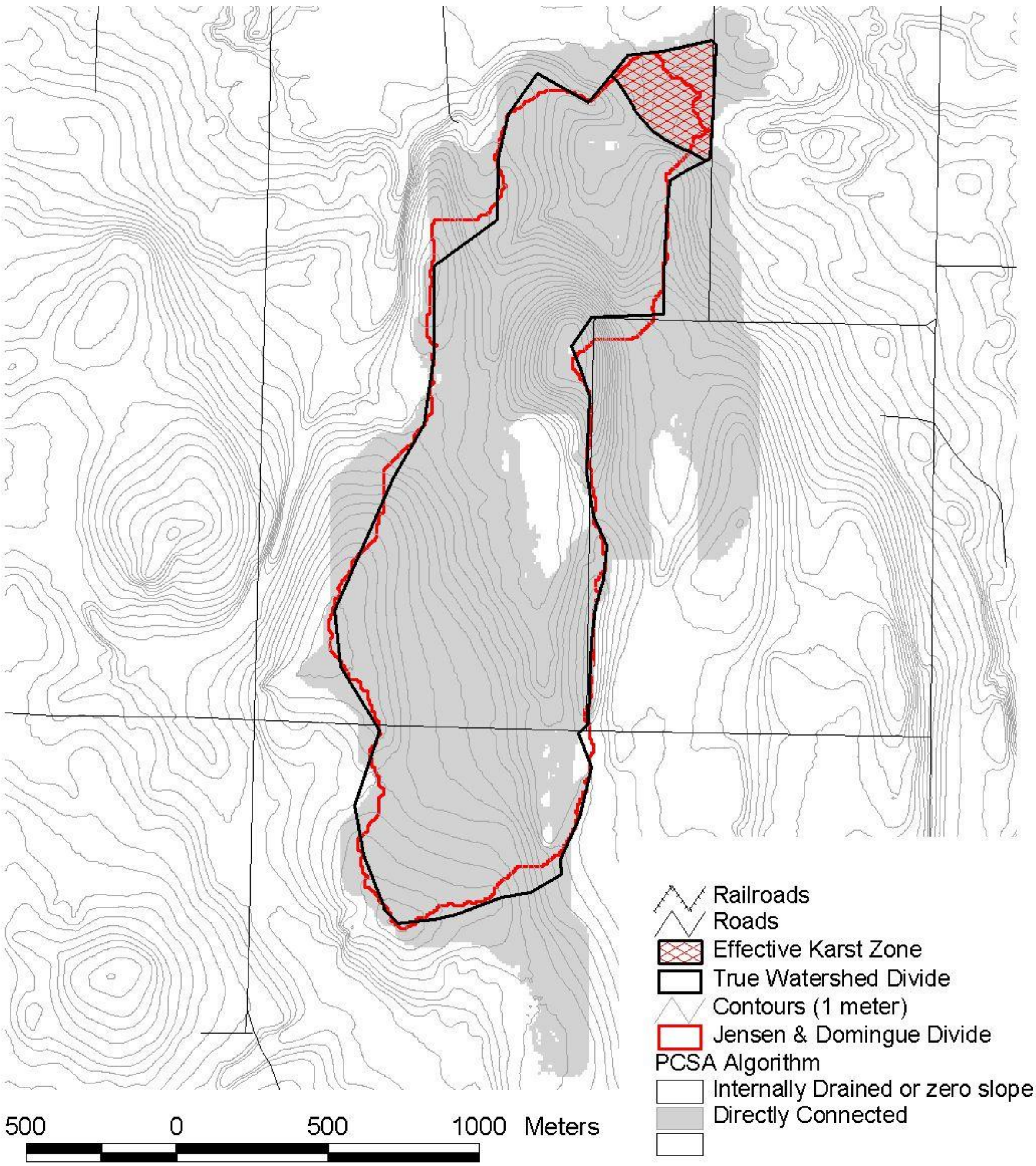

Figure 28 Site 55; a patterned ground sinkhole.

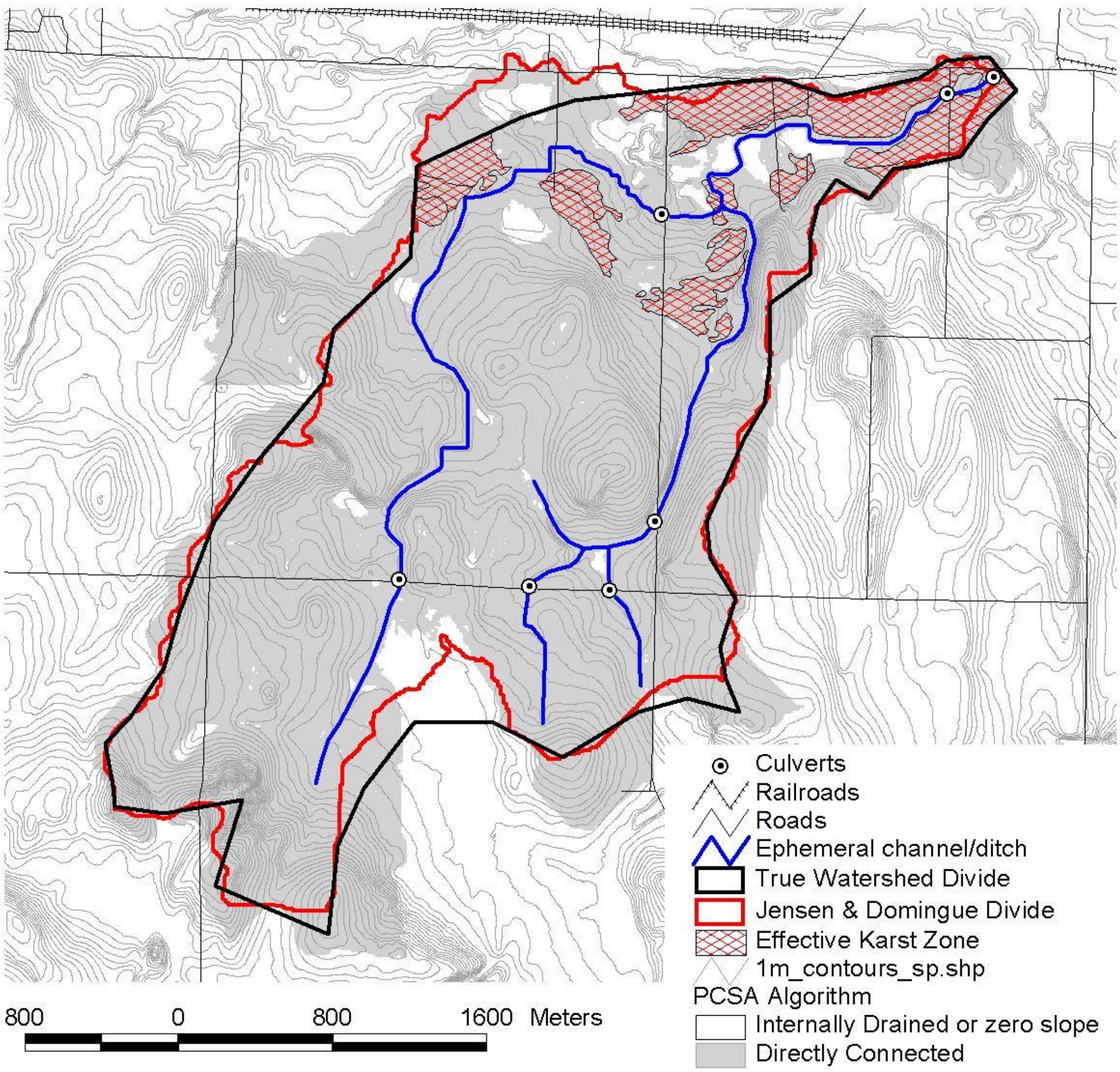

Figure 29 Site 56; a patterned ground sinkhole.

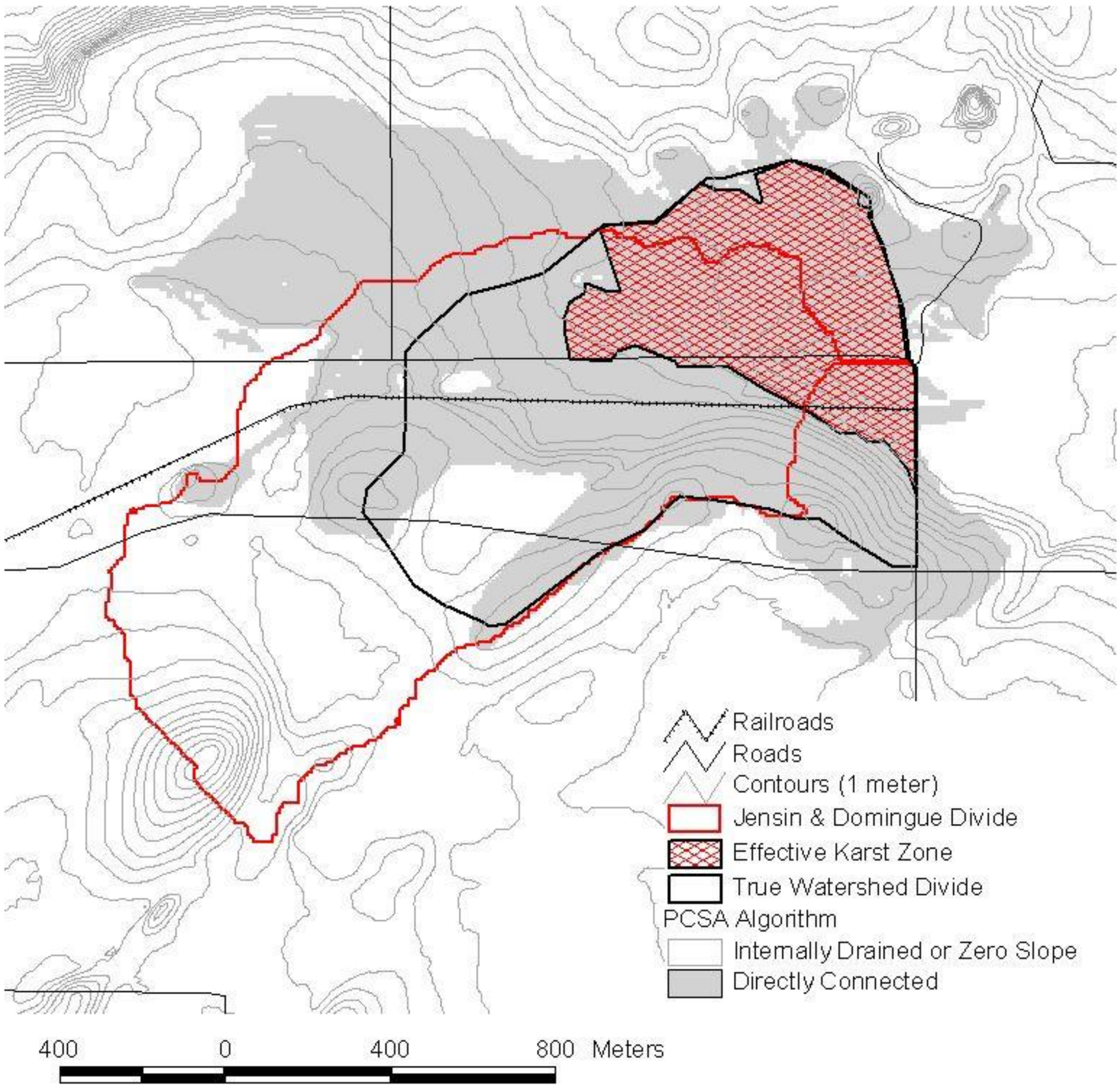

Figure 30 Site 58; the Britt Rd sinkhole. A glacially enhanced sinkhole system plagued by karst-related flooding.

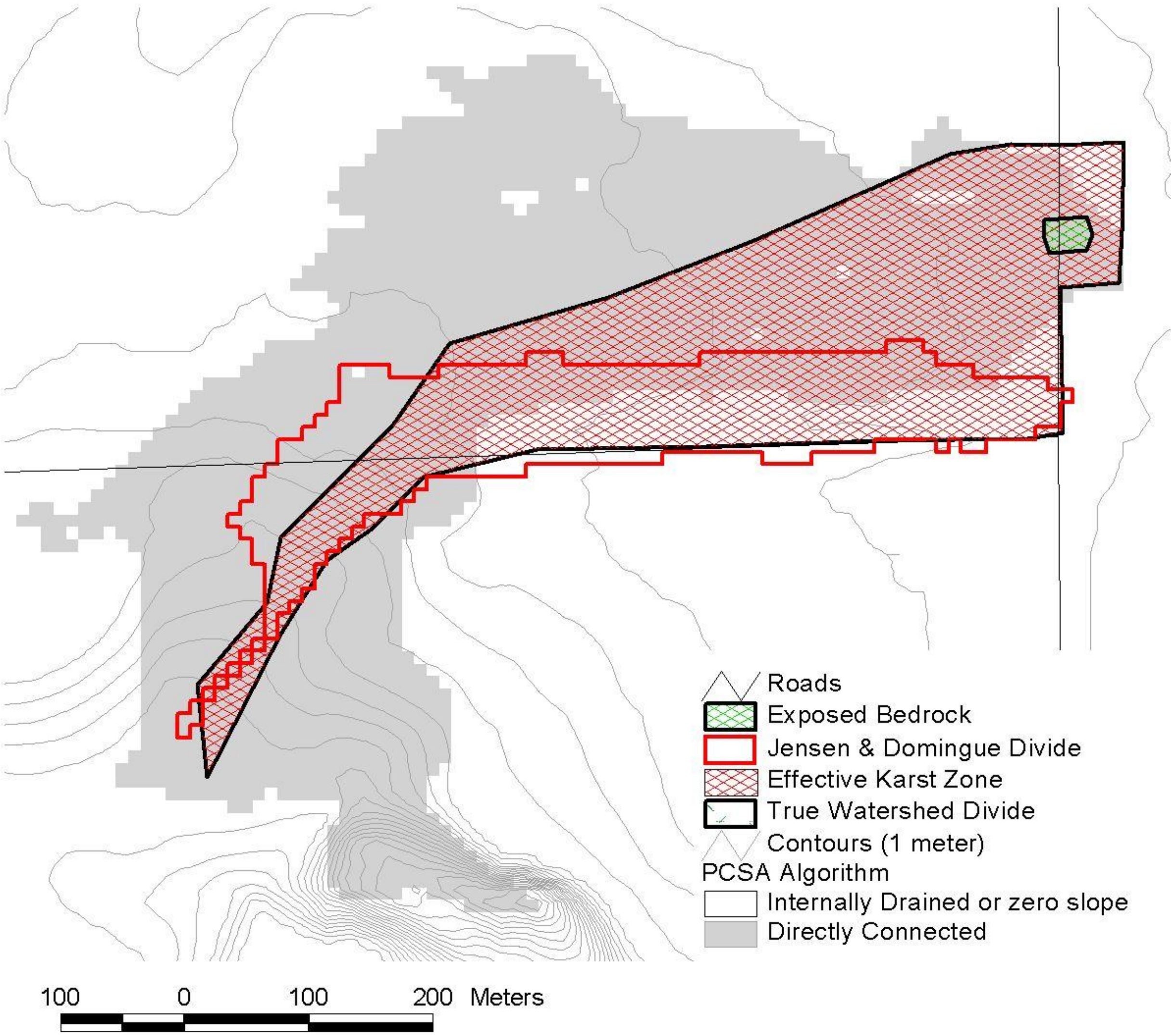

Figure 31 Site 62; an exposed fracture-bedrock zone. 100% of its watershed is covered with thin soils.