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Aquifer vulnerability changes due to faults and riverbeds in Salamanca, Guanajuato, Mexico

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RESUMEN

El crecimiento poblacional y el desarrollo agrícola e industrial han provocado sobre-explotación del acuífero local y consecuentemente subsidencia en la zona de Irapuato-Valle de Santiago, principalmente en la ciudad de Salamanca. El proceso de subsidencia ha originado fallas y fracturas que actúan como ductos preferenciales para contaminantes superficiales. El acuífero local es la única fuente de abastecimiento para la población de Salamanca. No hay cuerpos de agua superficiales. El río Lerma cruza la mancha urbana y divide hidráulicamente el acuífero local. El río recibe aguas residuales, urbanas e industriales sin tratar. El método del Índice de Vulnerabilidad Acuífera, AVI, fue usado en la mancha urbana. La falla y el cauce del río fueron incorporados en el método AVI. Un análisis de sensibilidad de estos factores fue realizado. La evaluación de vulnerabilidad AVI resultó más sensible a la presencia de la falla que a la del cauce del río.

PALABRAS CLAVE: Vulnerabilidad, Índice de Vulnerabilidad Acuífera AVI, subsidencia, fallas, Salamanca.

ABSTRACT

Subsidence due to pumping in Salamanca, Mexico causes faults and fractures that introduce pollutants into the groundwater. The local aquifer is the only source of water supply for Salamanca. The Lerma river receives untreated urban and industrial wastewaters. The Aquifer Vulnerability Index, AVI, is shown to be more sensitive to the fault than to the riverbed.

KEY WORDS: Vulnerability, Aquifer Vulnerability Index (AVI), subsidence, faults, Salamanca.

INTRODUCTION

Urban, agricultural and industrial development of Salamanca City in the state of Guanajuato, Mexico causes intense pumping of groundwater. There are more than 1600 active wells, of which 33 are for urban water supply. Excessive pumping causes compaction of a clayey lens that induces faulting and fracturing through which pollutants can reach the shallow aquifer containing fine grained sediments that facilitate dispersion of the pollutants.

The differential displacements created a fault that crosses the urban area to the NE with a length of over 12 km (Garduño, 2002). The fault causes damage in water pipelines and sewers. The fault allows water to seep from a shallow not exploited aquifer into a deeper aquifer which is being tapped. There is also a deep aquifer which is exploited by a thermoelectric power plant.

The Lerma river which crosses through the city, receives untreated urban and industrial wastewaters. The National Water Commission, CNA, classified it as "strongly contaminated" in the industrial corridor Celaya – Salamanca – Irapuato to "very strongly contaminated" after Salamanca City (Guysa, 1998). Locally the river recharges the shallow aquifer.

The study area is located in the Santiago valley, which belongs to the Transmexican Volcanic Belt. The surface sediments are of lacustrine and fluvial origin alternating with fine to medium residual soils. There are also volcanic and sedimentary rocks from Tertiary to Recent age (Rosales 2002).

The oldest formation recognized in outcrops and in well lithology is the Cuatralba formation (Nieto, 1992). This formation comprises ignimbrites and tuffs of felsic composition with breccias and fractures. The upper part of the formation contains well consolidated ignimbrites, and in the lower part there are poorly consolidated massive tuffs (Rosales, 2002).

The area has no known seismic activity. The regional tectonic framework controls the distribution and geometry of the clay and clayey units. Subsidence and intense water extraction have been correlated in other areas (Trujillo, 1991; Toufigh and Sabet, 1995; Chen *et al.*, 2003)

Since the early 80's faults and fractures have been reported in Salamanca. The main fault is considered a normal fault and the eastern block is down faulted. The mean subsidence velocity is 6 cm/year. The influence zone has been estimated at 50 m (Garduño, 2000). In Juventino Rosas, a small settlement NE of Salamanca, the accumulated subsidence is about 2 m.

The Lerma riverbed is the boundary of the local aquifer system. North of the river there are three aquifers, but in the southern area the shallow aquifer is not well defined. There are perched aquifers of small extension and irregular geometry. Locally the exploited aquifer is partly confined (Rodríguez *et al.,* 2001a). There is no evidence of the deep aquifer. The riverbed thus defines also two different geological environments: in the north fine-grained sediments prevail and in the south fractured volcanic rocks dominates.

THE AQUIFER SYSTEM

Groundwater quality in the shallow and intermediate aquifers in the northern zone is different. The water table of the shallow formation is located at a depth of 18-19 m and the piezometric level of the intermediate aquifer is 30-35 m. Hydrocarbons were detected in an urban well near the fault, thus showing that the fault is hydraulic communicating both formations polluting the intermediate aquifer. The well was closed. The confining layer is a crystalline clay with a thickness of 5-10 m.

The groundwater temperature of the deep formation is above 40° C and its piezometric level is 70-80 m deep. Its composition is fractured volcanic rock. There are no reports of hydraulic communication between the deep and the intermediate aquifer.

METHODOLOGY

The Aquifer Vulnerability Index, AVI (Van Stempvoort *et al.*, 1993), was estimated in the urban area of Salamanca. This aquifer vulnerability assessment only requires knowledge of the local stratigraphy and the hydraulic conductivity, k, for each layer of the vadose zone. The AVI index, a transit times, is calculated from the thickness, h, and the k values of each layer above the water table. The index is calculated for each of the wells. Data were interpolated using a Kriging algorithm. Data are presented in log of years. Short AVI times, in days, represent high vulnerability and long times, in years, low vulnerability.

Most vulnerability assessment methods do not consider inhomogeneities such as faults and fractures, which may alter the permeability of shallow formations. They may be incorporated by introducing the hydraulic conductivity (Rodríguez, 2003). Rivers, lakes, dams or other surface streams can also pollute aquifers when they present hydraulic communication with the aquifer. A riverbed can be incorporated through k data.

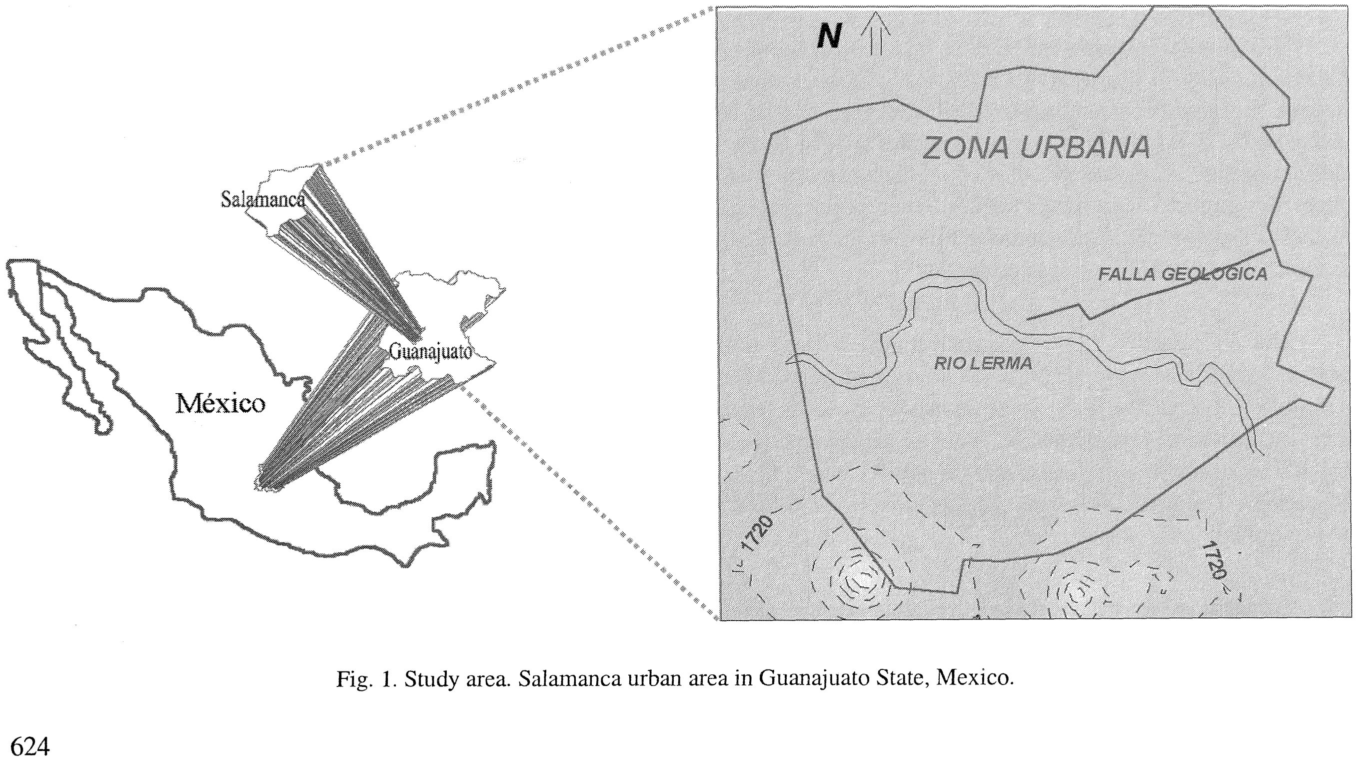

Fig. 1. Study area. Salamanca urban area in Guanajuato State, Mexico.

To understand how the incorporation of faults and the riverbed can affect an aquifer vulnerability assessment, a sensitivity analysis was performed. An initial AVI map was done without considering the fault and the riverbed (Figure 3a). This map contained 45 points with well data and six geological profiles that included also geoelectric information. Next a set of maps was developed considering the fault and the riverbed.

The hydraulic conductivity was estimated from 5 pumping test. To complete the data set, permeability measurements were done *in situ* with a constant head permeameter. 75 values were collected. Measurements were done along the fault and in both river margins. Sites with fractures and unaltered terrains were selected. Permeability tests were carried out also in the riverbed margins. Non-covered areas and zones with sediments along the riverbed were chosen for the measurements.

SCENERIES

The degree of fracturing level was different in each site and conductivity values also varied. Even in very similar conditions the k values varied by 20 % due to lithology, fracture density and soil type. Similar variations were obtained for k determinations along the riverbed. Scenario analyses were done considering such variations. A base map (Figure 3a) was elaborated without taking into account the fault and the riverbed. Other map incorporates the raw fault data and other two maps show the k values obtained along the fault, ± 20%. A similar procedure was applied to the riverbed. Others percentages of variation were considered. 10% produced no significant changes. Values of 15 % and 25 % presented quite similar results.

The scenarios were as follows:

- Base map with fault (Figure 2c).
- Base map with riverbed (Figure 2b).
- Base map with riverbed and fault (Figure 2d).
- Base map with riverbed + 20 % (Figure 3e) and - 20 %. (map Figure 3f).
- Base map with fault + 20 % (map Figure 3g) and - 20 % (map Figure 3h).

RESULTS AND DISCUSSION

Faults and fractures are not often incorporated in aquifer vulnerability assessments. At scales of 1:50,000 or smaller, it is not possible to see a 10 m length fault or fracture, but they become important at larger scales than 1:20,000. Their importance is greater in industrialized urban areas.

The Lerma river receives untreated urban and industrial waste waters. The riverbed crosses unconsolidated rocks. It is covered partially by impermeable fine sediments, mainly of organic matter. The hydraulic conductivity of the bottom is variable.

Aquifer vulnerability distribution changes when the fault and the riverbed are included in the vulnerability assessment. The riverbed crosses the central low vulnerability zone in the base map (Figure 3a) and constitutes a vulnerable area (Figure 2b). This area is located where k was relatively high due to the scarce presence of fine sediments. When the fault is considered, a zone of high vulnerability along the fault is defined (Figure 2b). The fault changes drastically the aquifer vulnerability, because it increases three orders of magnitude the hydraulic conductivity. Locally the fault can also lower the conductivity due to clay smearing or grain scale mixing (Bense *et al.*, 2003).

The fault and the riverbed were integrated through their hydraulic conductivity, it was measured *in situ*. The range of k variation was ± 20%, including measurement errors. The permeameter scale is in centimeters. Errors of 0.5 cm correspond to errors in conductivity of 4 %.

The river is a hydraulic barrier, but when it is incorporated in the base map, the low vulnerability area located below the riverbed decreases even more. If k increases by 20 % a vulnerability area of (-1.5) appears where a low slope does not permit sediment accumulation over the sandy riverbed.

The fault has an even greater impact in the vulnerability zoning. In some points the calculated transit time is only hours. The zone with high vulnerability located in the north is increased. Along the fault a very high vulnerability, approximately 100 m wide, is reported. The permeability of the original stratigraphy was altered. The fractured clay and clayey layers became permeable and the subjacent aquifer becomes vulnerable.

In the NW quadrant there are no significative changes (Figure 2b,c,d). In the SE quadrant the riverbed diminished the low vulnerability area of the base map (Figure 3a). The greater variations are observed in the NE quadrant (Figure 2d). The high vulnerability areas of the base map are connected with the fault. In the SW quadrant the vulnerability changes are correlated with the interpolation process rather than the riverbed presence.

The AVI vulnerability zoning showed more sensitivity to large changes in hydraulic conductivity due to the fault, than to the riverbed.

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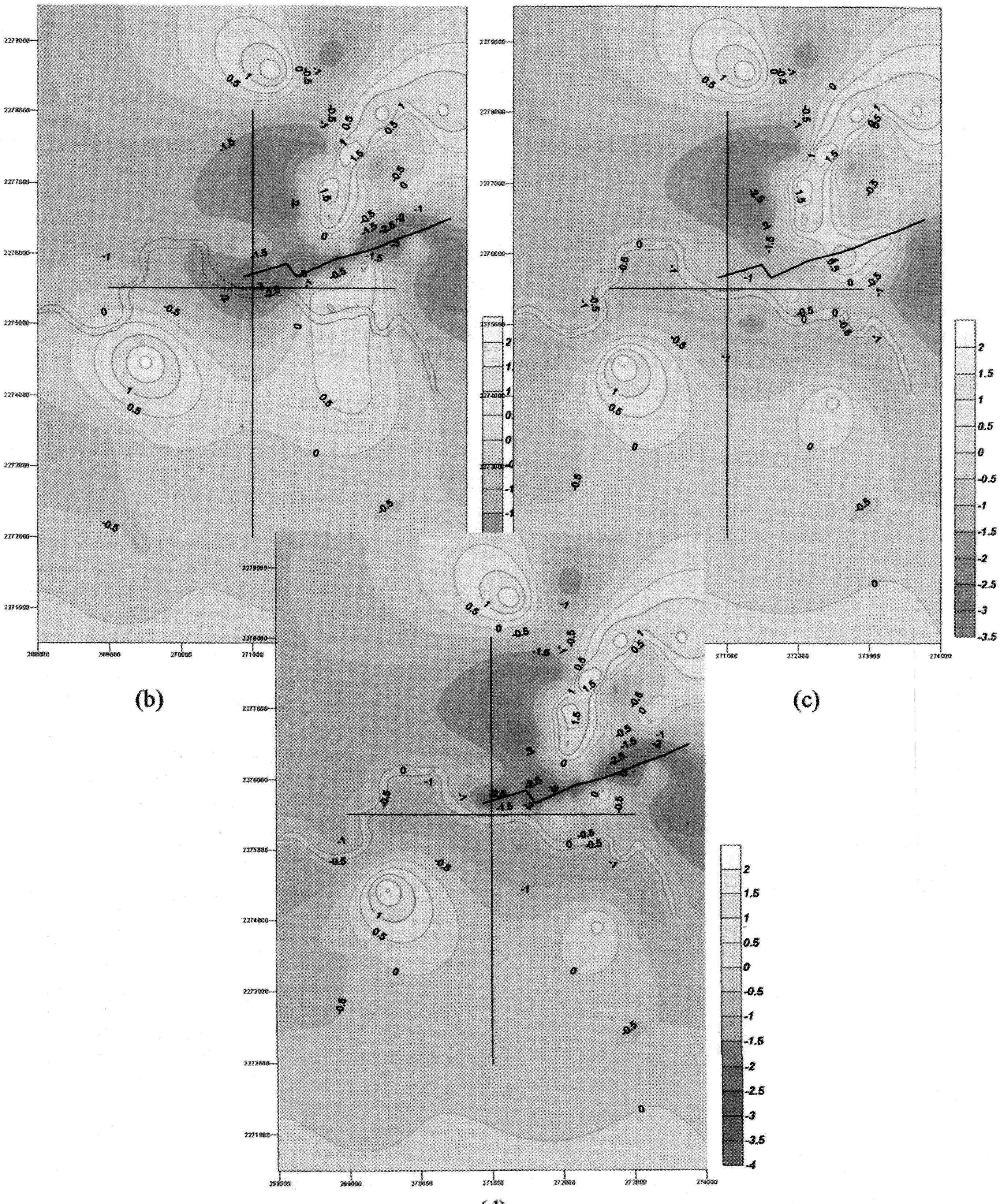

(b)

(c)

(d)

Fig. 2. (b) Base map with fault. (c) Base map with riverbed. (d) Base map with fault and the riverbed.

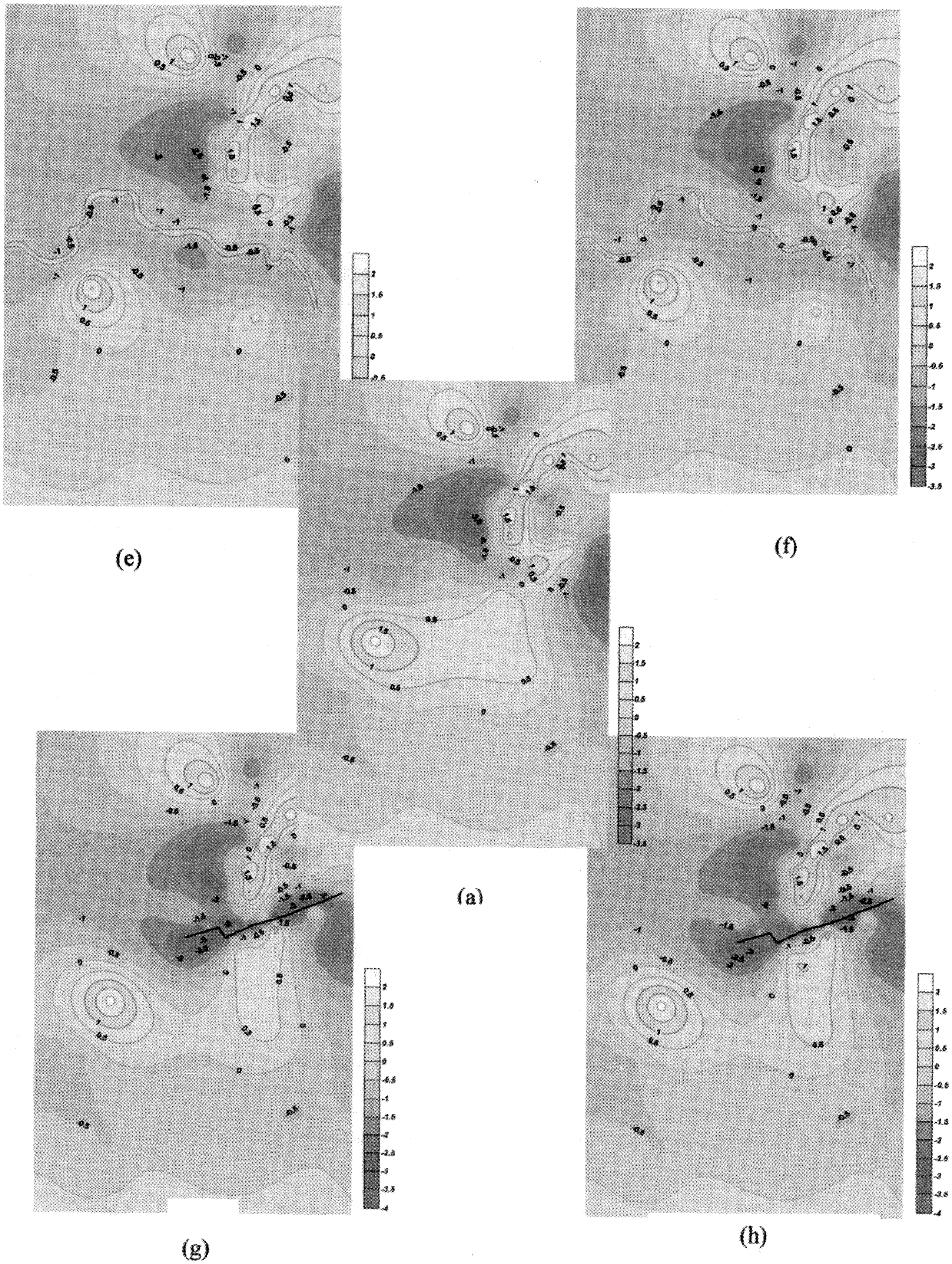

Fig. 3. (a) Base map. (e) Base map with riverbed + 20 %. (f) Base map with riverbed – 20%. (g) Base map with fault + 20%. (h) base fault with fault – 20%.

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