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Groundwater Recharge Estimation Using the GIS Tool, PRO-GRADE in Ma Keng Iron Mining Area, China

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Abstract: PRO-GRADE, an ArcGIS 9.2 plug-in was used to analyze groundwater patterns and estimate recharge rates in Ma Keng iron mining area, Fu Jian Province, China. The software consists of two separate packages, namely the Pattern Recognition Organizer for GIS (PRO-GIS) and Groundwater Recharge and Discharge Estimator for GIS (GRADE-GIS) for recharge pattern and rates estimation, respectively. Recharge rates estimated showed the distribution of recharge areas as 5.30, 11.03, 67.51, 6.38 and 9.78% for very high, high, medium, low and very low or no recharge, respectively. Recharge patterns extracted from recharge rate map showed almost similar results with its source map while those extracted from Digital Elevation Model (DEM) underestimated areas near river valleys. Generally, the area along Xi Ma River showed negative recharge meaning it maybe discharge zone.

Key words: Groundwater recharge, GIS, PRO-GRADE, GRADE-GIS, PRO-GIS

INTRODUCTION

Ma Keng iron mine is the largest mine in Eastern China, with a total iron storage in the iron ore deposit of about 434 million tons. The first phase of the project began in 2001 and the second phase started in 2008. Inspite of being at the initial stages but, environmental and ecological effects have already been observed (Hyandye *et al*., 2008; Traore *et al*., 2008). The presence of mining activities has attracted expansion of other human activities such as cement industries, agriculture, infrastructure development and increased population. These activities have either direct or indirect effects on the groundwater regime hence, groundwater monitoring is an important aspect.

Moreover, the extent of mining activities in Ma Keng involve surface mine specifically for limestone minerals and deep mine (extending from 100-1000 m tunnels) for iron. In addition, about 30,000 cubic meter of groundwater is pumped out from the deep tunnels daily. Principally, the sustainability of an aquifer and the survival of living organisms in the surrounding area depend on the amount of water stored under the soil surface (underground water). The status of an aquifer does not affect only biotic things but also the morphological structure of the area. For example, too much water withdraw has caused land depression in some places in the world such as Mexico city in 1970 (Freeze and Cherry, 1979), Suzhou city and North China plain in China (Liu *et al*., 2001). In Ma Keng, the extent which mining activities pose to groundwater quantity is still unknown and not yet studied. This study aimed at investigating the recharge pattern and rates, which are major components of groundwater quantity in the aquifer.

Estimation of groundwater recharge requires huge amounts of data because it depends on numerous factors ranging from climatic, topographic, land cover, soil and rock formations (Stoertz and Bradbury, 1989; Wu *et al*., 1996; Scanlon *et al*., 2002; Memon, 1995; Delin *et al*., 2000, 2006). It is also complex, difficult and time-consuming procedures especially for an area that has not previously been studied like the Ma Keng area (Risser *et al*., 2005; Stoertz and Bradbury, 1989). Computer simulation models for groundwater provide a solution especially in carrying out numerically initial estimations of recharge with readily available data (Dripps and Bradbury, 2007; Lin and Anderson, 2003). These lays a foundation for further intensive and extensive studies. Among the recently proposed approaches is the use of PRO-GRADE software (Lin *et al*., 2008).

PRO-GRADE, which is an Environmental Systems Research Institute (ESRI) ArcGIS 9.2 plug-in tool provides the solution for quick estimation of groundwater recharge (Lin *et al*., 2008). It requires data of hydraulic conductivity, water table and bedrock elevations. The

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software consists of two separate programs, the Pattern Recognition Organizer for GIS (PRO-GIS) and the Groundwater Recharge and Discharge Estimator for GIS (GRADE-GIS). PRO-GRADE adheres to the default raster file developed by ESRI and uses ArcObjects library for spatial data access and mapping. If the input raster files (water table, conductivity and bedrock elevations) have equal number of cells, which have the same size. Hence, the vector quantity (i, j) for each cell are calculated using two dimensional stead state, mass balance equation (Lin *et al*., 2008 a, b).

The Eq. 1 is as follows:

$$Qin = R_{i,j} \Delta X_{i,j} . \Delta Y_{i,j}$$

$$Qin = Qin_{\_west} + Qin_{\_east} + Qin_{\_north} + Qin_{\_south}$$

$$Qin_{\_West} = \frac{h_{i-1,j} - h_{i,j}}{\Delta X_{i-1/2,j}} . K_{i-1/2,j} . b_{i-1/2,j} . \Delta Y_{i,j}$$

$$= \frac{h_{i-1,j} - h_{i,j}}{\Delta x_{i-1/2,j}} . T_{i-1/2,j} . \Delta Y_{i,j}$$

$$Qin_{\_east} = \frac{h_{i+1,j}}{\Delta x_{i+1/2,j} . K_{i+1/2,j}} . b_{i+1/2,j} . \Delta Y_{i,j}$$

$$= \frac{h_{i+1,j} - h_{i,j}}{\Delta X_{i+1/2,j}} . K_{i,j} . T_{i+1/2,j} . \Delta Y_{i,j} \qquad (1)$$

$$Qin_{\_north} = \frac{h_{i,j+1} - h_{i,j}}{\Delta Y_{i,j-1/2}} . K_{i,j+1/2} . b_{i,j+1/2} . \Delta X_{i,j}$$

$$= \frac{h_{i,j+1} - h_{i,j}}{\Delta Y_{i,j+1/2}} . T_{i,j+1/2} , \Delta X_{i,j}$$

$$Qin_{\_south} = \frac{h_{i,j-1} - h_{i,j}}{\Delta Y_{i,j-1/2}} . K_{i,j-1/2} . b_{i,j-1/2} . \Delta X_{i,j}$$

$$= \frac{h_{i,j-1} - h_{i,j}}{\Delta Y_{i,j-1/2}} . T_{i,j-1/2} , \Delta X_{i,j}$$

Where,

$\Delta x_{ij}, \Delta Y_{ij}$ = Horizontal cell dimensions (L); ΔX_{ij} and Δy_{ij} with ±1/2 in i and j represent the lengths between centers of cell (i, j) and its four adjacent cells (L)

R_{ij} = The recharge and discharge rate of cell (i, j) (L/t)

h_{ij} = The hydraulic head (water table elevation) of cell (i, j) (L)

T_{ij} = The transmissivity of cell (i,j), $T_{ij} = K_{ij}, b_{ij}$ for unconfined aquifer (L^2/t)

K_{ij} = The hydraulic conductivity of cell (i, j) (L/t)

b_{ij} = The saturated thickness and is equal to hydraulic head minus bedrock elevation (L)

$T_{i+1/2,j}$ = The harmonic mean of transmissivity between cell (i + 1, j) and cell (i, j) (L^2/t)

MATERIALS AND METHODS

Study area: The study site is Ma Keng iron mining area, which is located in Caoxi town, Xinluo district in Longyan city of Fu Jian Province, China. It lies between longitude 117°2'30"-117°6'04"East and latitude 25°0'0"-25°3'30"North. For this study, an area of 36.51 km^2 was covered. The landform is described as mountainous with steep slopes, hills and valleys. The highest elevated point is 1100 m, while the lowest is 400 m above sea level. Evergreen coniferous, broad leaf plants, shrubs, grasslands and deciduous forest mainly covered by bamboo plants, characterize the vegetation cover of the site. Xi Ma River, which cuts through the site from Northwest to South and its tributaries characterize surface water distribution. Vegetation along the river is influenced by agricultural activities such as vegetable gardens and seasonal plants mostly rice. Human settlements, industrial buildings and road networks form part of the impervious surface and are concentrated along Xi Ma river valley (Fig. 1).

Groundwater recharge studies reflect much on the nature and characteristics of the area especially on elevation, geology, land-surface slope, vegetation and climatic factors (Healy and Cook, 2002; Freeze and Cherry, 1979). Ma Keng mining area falls under subtropical-monsoon climate, which experience warm and humid

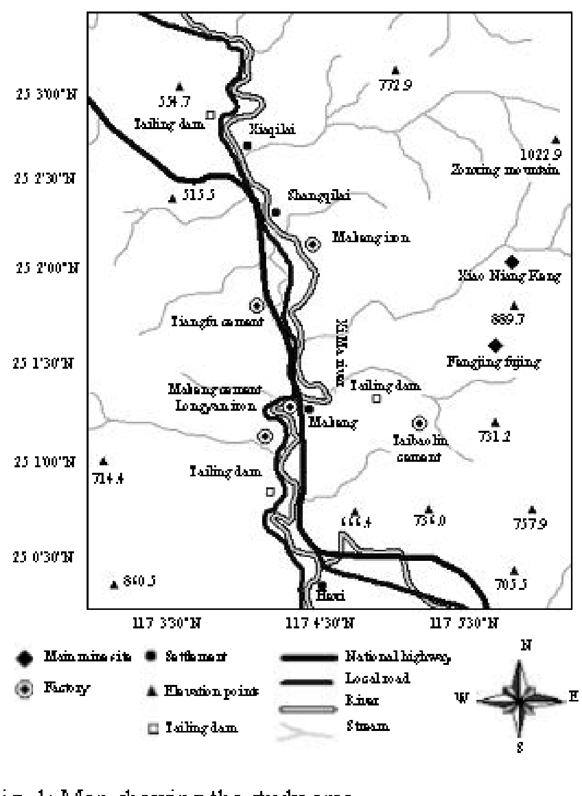

Fig. 1: Map showing the study area

weather. The average annual rainfall is 1692 mm. The rain season starts from May through August and dry season from September to December. January and February are winter snow periods, while March and May is transitional season. During the months of May and August, rainfall constitutes about 60% of total annual precipitation. The average annual temperature is 19.9°C, the minimum day temperature is -5.6°C in winter and the maximum day temperature is 38.1°C during summer. The total sun illumination is about 1979.1 h year^{-1} (Hyandye *et al.*, 2008; Traore *et al.*, 2008).

Data source: Maps for water table (measured on 23 August 2008), bedrock elevations, Digital Elevation Model (DEM) and geological map (scale 1:5000 prepared in 2007 were obtained from 3S laboratory, School of environmental studies, China University of Geosciences. A field study of 12 days (25 November to 10 December 2008) was conducted for site familiarization. Geographical Positioning System (GPS) assisted in locating and plotting necessary features (surface water, land uses, vegetation and points where soil samples were taken).

In addition, the field survey involved collection of soil samples from ten different sample points where 132 samples were collected at 0.2 m intervals from the land surface to 3 m depth.

PRO-GRADE software estimates recharge rates based on saturation thickness (water table to bedrock) and hydraulic conductivity of soil or aquifer media. Hence, the input maps were prepared in ArcGIS 9.2 and converted to grid format as necessitated by PRO-GRADE.

Hydraulic conductivity: Hydraulic conductivity was determined from grain-size distribution analysis method, using a Kozeny-Carman empirical Eq. 2 as explained by Odong (2007). Laboratory researches were done at groundwater laboratory, school of environmental studies, China University of Geosciences. Grain sizes were separated using standard sieves and their masses measured. Results were recorded in laboratory sheets and then typed in Microsoft office for compilation and computation (Table 1 and 2).

Kozeny-Carman Eq. 2:

$$K = \frac{g}{v} \times 0.0083 \times \left[\frac{n^3}{(1-n)^2}\right] \times d_{10}^2 \tag{2}$$

Where,

K = Hydraulic conductivity
g = Acceleration due to gravity
v = Kinematic viscosity
n = Porosity
d_{10} = Tenth grain diameter

Thereafter, a hydraulic conductivity map was prepared in ArcGIS 9.2 shapefile format and the steps following:

- Map features were converted to floating points in ArcToolbox of ArcMap
- Feature-points were interpolated to raster in spatial analyst tool

The interpolation processing options were set to spline, tension, weight 0.1. Number of points set to 12 and output cell size set to 20. It was assumed that the distribution of hydraulic conductivity from sample points represented its surrounding area as distributed by floating points (Fig. 2).

Water table and bedrock elevations: The maps obtained were in shapefile contour format, which is compatible with ArcGIS. Therefore, they were imported into ArcCatalog and then ArcMap for geocorrection and coordinate projection. The co-ordinate projection for all maps was

Table 1: Summary of grain sizes distribution

	Grain diameter (mm)						
Sample points	<0.074	0.074-0.25	0.25-0.5	0.5-1	1-2	2-5	5-10
1	1.5625	2.057142857	1.061904762	2.2	1.41875	2.8125	1.5625
2	0.1	1.5	0.6	0.7	0.7	1.4	1.8
3	0.2	1.1	0.3	0.3	0.3	0.5	0.2
4	0.1	2.6	1.8	2.3	1.6	1.0	0.3
5	0.4	3.1	1.0	1.3	1.6	3.6	2.0
6	0.1	2.9	1.6	1.8	1.5	2.0	2.0
7	0.2	2.9	1.2	1.4	1.4	2.0	1.3
8	0.2	2.7	1.0	1.2	1.1	1.9	1.6
9	0.2	2.9	1.0	1.1	1.1	1.5	1.2
10	1.3	6.8	0.9	0.7	0.7	1.1	0.1

Table 2: Estimated hydraulic conductivity by Kozeny-Carman equation

Sample points	Soil classification	Conductivity (m day^{-1})
1	Medium sand	45.138
2	Coarse sand	52.882
3	Fine sand	18.433
4	Medium sand	28.017
5	Gravel sand	96.251
6	Gravel sand	104.546
7	Coarse sand	73.339
8	Coarse sand	68.345
9	Medium sand	16.112
10	Fine sand	4.328

Fig. 2: Hydraulic conductivity in grid raster format

synchronized to WGS_1984_UTM_Zone_50N Co-ordinate System. These were then converted into floating points and interpolated to raster format as it was done for conductivity map (Fig. 3 and 4). PRO-GRADE software requires all input maps be synchronized into the same coordinate system with equal number of grids (cells) of equal cell size.

For this case, all maps contained same cell size (x, y) 20, 20 and same grid number 87636 (columns 268 and rows 327).

GRADE-GIS processes: This was done by successful preparation of the required input maps (steps described schematically in Fig. 5), then GRADE-GIS Graphical User Interface (GUI) was launched in ArcMap 9.2. conductivity, water table and bedrock elevations raster files inputted into their respective locations as required by the software.

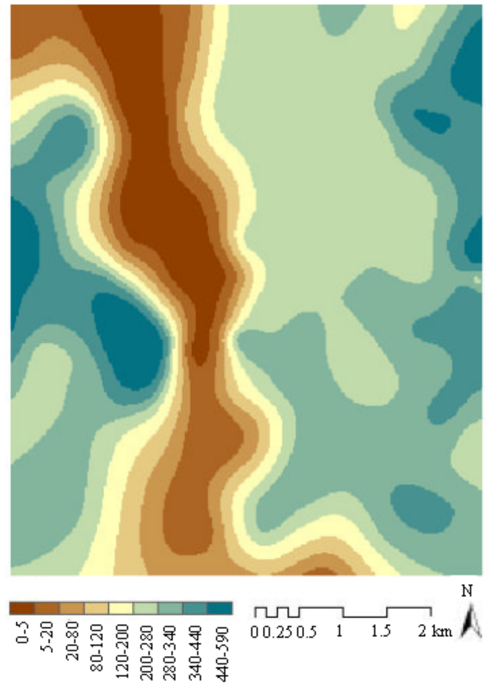

Fig. 3: Water table levels in grid raster format

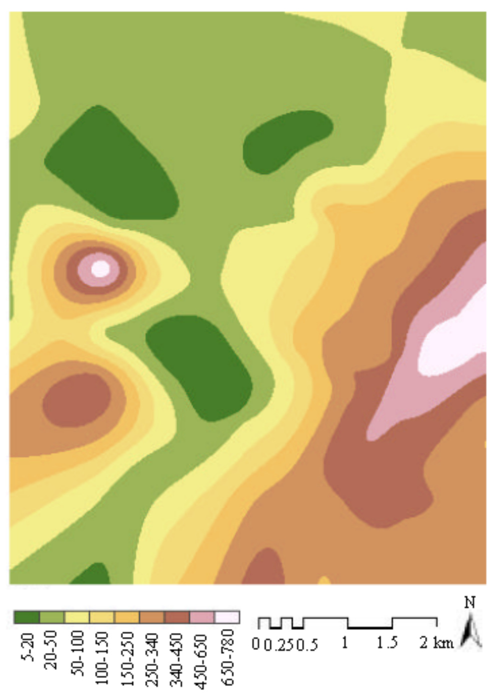

Fig. 4: Bedrock elevations in grid raster format

Recharge pattern analysis: Recharge pattern analysis was done by executing DEM and groundwater recharge estimate map (GRADE-GIS output) separately into

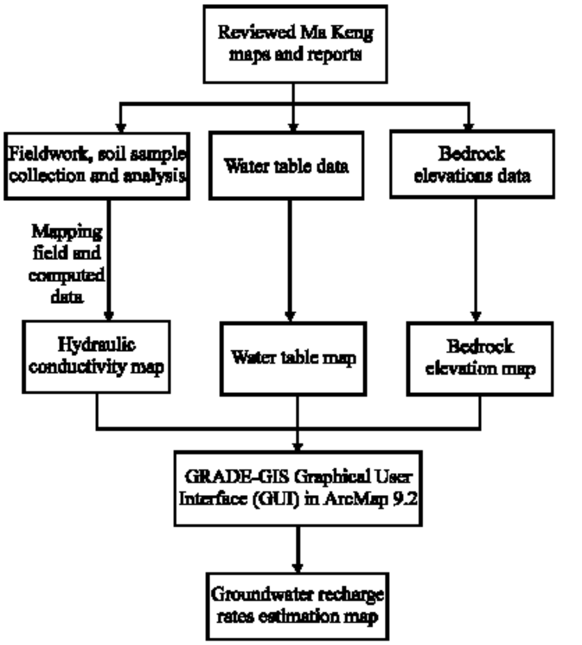

Fig. 5: Data processing steps for estimation of recharge rate using PRO-GRADE

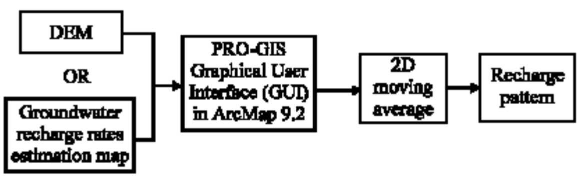

Fig. 6: Steps of processing recharge pattern using PRO-GRADE

PRO-GIS User Interface (Fig. 6). Then, 2D moving window average processing was adopted, focal statistics and aspect ratio of width and height locked at 4, 4.

RESULTS AND DISCUSSION

Groundwater recharge rates: The results of (Fig. 7) shows that recharge takes place in most areas but highly in some places near Xi Ma river valley, north-west, some of middle areas and eastern parts. Areas along the river valley had no recharge; probably they are discharge areas as suggested by Lin, Bradbury, Stoertz and others that areas, which appear with negative recharge, are discharge areas (Lin *et al.*, 2008a, b; Stoertz and Bradbury, 1989).

The recharge area distribution (Table 3) shown that 5.30, 11.03, 67.51, 6.38 and 9.78% had very high, high, medium, low, very low or no recharge, respectively (Table 3). In the real sense, groundwater recharge amount

Table 3: Recharge area distribution

Recharge rate classification	Area (ha)	Percentage
Very high	193.51	5.30
High	402.72	11.03
Medium	2464.88	67.51
Low	232.94	6.38
Very low or no recharge	357.08	9.78
Total	3651.13	100.00

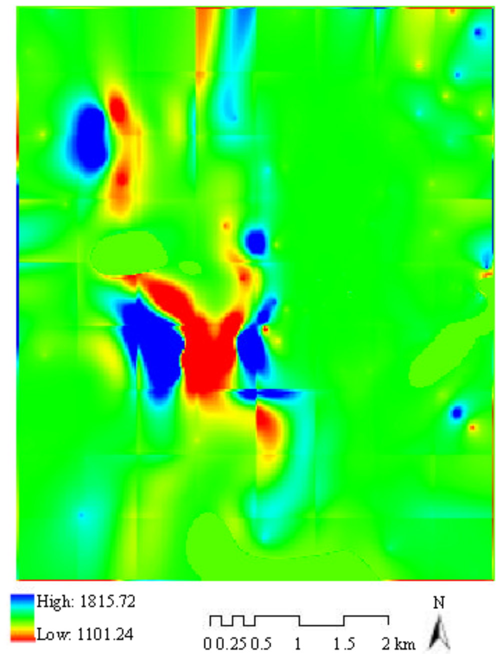

Fig. 7: Estimated groundwater recharge rates. Deep blue: Very high, Light blue: High, Green: Medium, Yellow: Low, Red: Very low or no recharge

depend on the, amount, intensity and duration of precipitation. These results mean that during precipitation fall, the recharge amount will be high in areas with higher rates and low or no recharge in areas with lower rates.

Groundwater recharge pattern: Recharge patterns recognized from Digital Elevation Model (DEM) and GRADE-GIS output (Recharge rate map) showed different results (Fig. 8).

In both cases, however, it is shown that the area along Xi Ma river valley has negative recharge, signifying that there is no recharge-taking place and were considered as no recharge or discharge zone. Eastern parts and most of West and North West parts are higher recharge zones while, the rest are medium recharge zones. However, patterns recognized from DEM show distribution of recharge areas escapes the coverage of surface water.

Also, it under-estimated the eastern parts near river valley. This is due to fact that DEM comprises only of

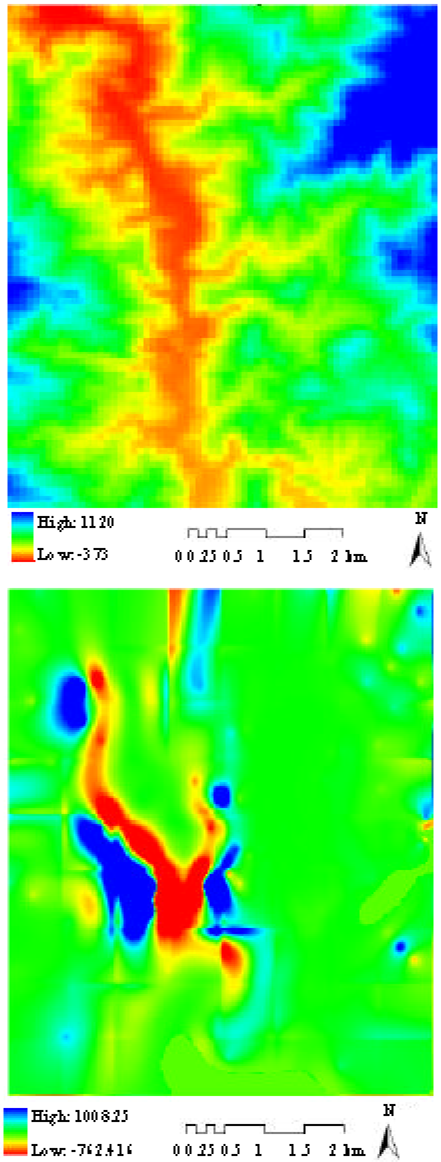

Fig. 8: Groundwater recharge patterns analyzed from DEM (left) and from recharge rate map (right). Deep blue: Very high; Light blue: High, Green: Medium, Yellow: Low, Red: Very low or no recharge

topographic data hence, it neglects other factors such as saturation thickness. Recharge patterns extracted from the map of recharge rate showed much resemblance to its source map. It is important to note that hydraulic conductivity does not affect recharge patterns (Stoertz and Bradbury, 1989) but affects recharge rates.

These results mean that, PRO-GRADE software provides good results for precipitation recharge estimation, based on saturation thickness and hydraulic conductivity. Therefore, areas with shallow water table are viewed as no or negative recharge zones. For this case, the software should only be used in humid climate not in arid and semi-arid regions where recharges take place around or along surface water because of little or absence of precipitation.

CONCLUSION

This research study aimed at providing initial estimation of groundwater recharge rates and its patterns in Ma Keng. PRO-GRADE software and ArcGIS 9.2 worked successfully by using few data, mainly hydraulic conductivity, bedrock elevations, water table and Digital Elevation Model. Results revealed that areas around or along surface water comprise non-recharge zones while in other parts recharge rate varied from medium to high. Ma Keng iron mining area is mountainous, occupied by mining sites for iron (deep mine) and limestone (surface mine), agriculture and human settlements all of which affect the natural recharge pattern and rates. Hence, regular intensive and extensive studies on groundwater quantity and quality are necessary. Furthermore, future studies should pay attention on the differences of recharge rates, especially during selection of points for installation of equipments. Therefore, these results lay a foundation for further groundwater recharge modeling and field-based studies. Conclusively, from these results, PRO-GRADE should not be used in arid and semi-arid regions because it will over estimate recharges in uplands and underestimate in areas around or along surface water bodies.

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