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Solving Three Problems of Exploration and Engineering Geology by Digital Terrain Analysis

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ABSTRACT

In the smooth-surface approximation, local accumulation of a flow is controlled by relative deceleration and convergence. Flow deceleration is determined by vertical curvature of the land surface, while flow convergence is controlled by horizontal curvature. There is a concurrent action of flow convergence and relative deceleration at areas marked by negative values of both of these curvatures. These areas are said to be relative accumulation zones. We describe basic principles of applying maps of relative accumulation zones to solve three problems of exploration and engineering geology: (1) exploration of alluvial placers; (2) prediction of landsliding on reservoir shores; and (3) prediction of soil degradation and contamination along pipelines. The deposition of placer minerals is most likely to occur in relative accumulation zones with slope steepness below 3°, all other factors being equal. The activation of slope instability is most probably to occur in relative accumulation zones with slope steepness beyond 15°, which are adjacent to, upslope the reservoir water level. Soil degradation (waterlogging and salinisation) may be observed in relative accumulation zones adjacent to, upslope a pipeline. After the pipeline failure, one can use a map of specific catchment area to determine paths of lateral migration of petroleum in the landscape. Petroleum products are most likely to concentrate in relative accumulation zones situated along a flow line originating at a pipeline hole. To refine the prediction, one should analyse accumulation zone maps together with geological, geophysical, geochemical, soil, plant, and remotely sensed data as well as with models of other topographic variables.

Keywords: Digital Terrain Model, Accumulation, Placer, Reservoir, Landslide, Pipeline, Soil, Degradation, Contamination.

Mathematics Subject Classification: 62H99, 62P12, 86A05, 86A60, 86A30.

JEL Classification: Q19, Q50.

INTRODUCTION

There is a concept of relative accumulation zones in geomorphometry and digital terrain modelling. In the smooth-surface approximation, the velocity of a gravity-driven flow varies in proportion to the slope factor (sin G). G, slope steepness, is an angle between a tangent and horizontal planes at a given point on the land surface. The local accumulation of a flow is controlled by two mechanisms, relative deceleration and convergence. Relative deceleration of a flow is determined by vertical curvature (k_v). k_v is the curvature of a normal section including the gravity acceleration vector at a given point. A flow tends to accelerate when $k_v > 0$, and to decelerate when $k_v < 0$. Convergence of a flow is controlled by horizontal curvature (k_h). k_h is the curvature of a normal section, which is perpendicular to the normal section with k_v. A flow diverges when $k_h > 0$, and converges when $k_h < 0$. Digital models of G, k_v, and k_h are derived from digital elevation models (DEMs). Details and formula can be found elsewhere (Shary et al., 2002).

There is a concurrent action of convergence and relative deceleration of flows within areas characterised by both $k_h < 0$ and $k_v < 0$. These areas are said to be relative accumulation zones. If divergence and relative acceleration of flows act simultaneously ($k_h > 0$ and $k_v > 0$), these areas are referred to as relative dissipation zones. Areas with other combinations of k_h and k_v signs are lumped together as transit zones. It should be noted that we consider zones of *relative* accumulation rather than dead-end depressions. A flow may pass through a great quantity of relative accumulation zones before entering into a dead-end depression. Models of k_v and k_h are used to derive maps of relative accumulation zones.

Maps of relative accumulation zones represent areas where geometrical peculiarities of the relief provide conditions for the local accumulation of gravity-driven substances, such as water (meteoric water, soil moisture), dissolved and suspended substances (salts, clay and organic particles, etc.), and other liquids (e.g., petroleum products). Maps of relative accumulation zones are used to solve various practical and fundamental problems of geosciences: prediction of slope instability (Lanyon and Hall, 1983), studies of lateral migration of artificial radionuclides in landscapes (Gurov and Kertsman, 1991), studies and modelling of soil properties at a field scale (Pennock et al., 1987; Florinsky et al., 2002; Shary, 2005), predictive soil mapping at small scales (Florinsky et al., 2000; Florinsky and Eilers, 2002), and studies of forest ecosystems (Shary, 2005). Relative accumulation zones may coincide with intersections of lineaments, faults, and fracture zones (Florinsky, 1993), and thus they constitute areas of contact and interaction of overland lateral flows and ascending and descending flows of groundwater and fluids (Florinsky, 2000). Maps of relative accumulation zones are usually used together with geological, geochemical, soil, plant, and remotely sensed data as well as with digital models of other topographic variables (e.g., slope gradient, catchment area).

In this paper, we describe basic principles of applying maps of relative accumulation zones to solve three problems of exploration and engineering geology: (a) exploration of alluvial placers; (b) prediction of landsliding on reservoir shores; and (c) prediction of soil degradation and contamination along pipelines.

EXPLORATION OF ALLUVIAL PLACERS

Placers are important sources of valuable minerals (Edwards and Atkinson, 1986). Alluvial placers are formed by chemical and physical weathering of primary deposits, subsequent transportation of mineral grains and crystals by water, and their deposition in valleys and channels (Bilibin, 1956; Macdonald, 1983; Shilo, 1985). Alluvial placers, constituting strip-like sand and gravel deposits located along valleys, range in length from 3 to 6 km, and in width from 10 and 100 m (Bilibin, 1956).

Relief influences formation of alluvial placers. The deposition of placer minerals usually occurs in areas where topographic characteristics offer deceleration of water currents and concentration of suspended particles (Bilibin, 1956; Macdonald, 1983). To find these sites, geologists commonly use a visual analysis of topographic maps (Muzylev, 1954). In terms of geomorphometry, desired areas correspond to relative accumulation zones marked by low values of sin G. Some methods of digital terrain analysis (e.g., derivating maps of flow line direction and catchment area) are utilised to model the formation of alluvial placers (McFarlane, 2000). However, up to now, maps of relative accumulation zones have not been used to search placer deposits.

To exemplify a basic principle of the implementation of relative accumulation zone maps, we consider a low-mountain area. The area size is about 4 by 4 km. A square-gridded DEM of the study area has a mesh size of 10 m (Fig. 1a). There is a primary deposit of some placer mineral in sources of two valleys, in the southeastern corner of the study area. A type of the mineral is not critical. The primary deposit is a source of placers in the two valleys. What is wanted is the location of placers.

To reduce a high-frequency noise, we applied three iterations of smoothing to the DEM using 5×5 kernel with squared inverse distance weights. Digital models of slope factor (Fig. 1b), horizontal curvature (Fig. 1c), and vertical curvature (Fig. 1d) were derived from the smoothed DEM by the method of Evans (1980). Models have a resolution of 10 m. A map of relative accumulation, transit, and dissipation zones (Fig. 1e) was obtained using k_v и k_h models.

It is known that the distribution of placer productivity along a valley depends on a stream gradient, all other factors being equal. For example, in the Lena Gold Placer Region (Siberia, Russia), up to 93% of the metal are located within areas marked by $G < 3°$ (Shilo, 1985). In the following analysis, we will utilise this threshold. It corresponds to $\sin G \approx 0.05$. The slope factor map (Fig. 1b) demonstrates that areas of $\sin G \leq 0.05$ are long and narrow strips located along thalwegs and water divides. Hereafter, we will consider only two valleys rising in the area of the primary deposit. In these valleys, let us to delineate sites of $\sin G \leq 0.05$ located within relative accumulation zones (Fig. 1e), which are situated downslope the primary deposit. As a result, we can obtain a map of sites where local geometry of the relief creates good conditions to form placers (Fig. 1f).

The prospective areas range in length from 100 to 150 m, and in width from 10 to 30 m (Fig. 1f). The areas form chains with a total length of about 4 km beginning from the primary deposit. To refine the map obtained, one should consider a density value of a particular mineral, its mineral resistance to chemical and mechanical erosion, and a settling rate, a function of specific gravity of a mineral, grain size and shape, and some other factors (Macdonald, 1983). These parameters may influence a threshold value of $\sin G$, and a distance that grains and crystals are moved from the primary deposit, that is, a total length of a chain of prospective areas. To adjust the map obtained, one may use results of geological, geomorphological, geochemical, and geophysical ground surveys as well as remotely sensed data.

In placer exploration, conventional visual analysis of topographic maps is rather subjective. Its results depend on the experience and intuition of a geologist. This leads to missing of prospective areas. Application of maps of relative accumulation zones can assist to plan prospecting grids and to reduce a cost of exploration. The principle described can be also used to reveal a modern alluvial placer formed due to erosion of a palaeo-placer rather than a primary deposit. Besides, the principle may be applied to search placers of ancient valleys uplifted by vertical tectonic movements and currently located on water divides. This may be favoured by the ability of digital terrain modelling to discover previously unknown, relict drainage networks (Almeida Filho et al., 2005).

PREDICTION OF LANDSLIDING ON RESERVOIR SHORES

It is well known that the filling of a reservoir and fluctuation of the reservoir water level amplify slope instability renewing old landslides and provoking new slope movement. Slope instability on reservoir shores is triggered by (a) water erosion of footslopes; (b) saturation of slope sediments due to the rise of groundwater; (c) weathering of sediments because of their periodical moistening and drying caused by the water level fluctuation; and (d) increase of the groundwater hydrodynamic pressure during rapid changes of the reservoir water level (Minervina and Khositashvili, 1974; Záruba and Mencl, 1982; Finarov, 1986). The life of a reservoir may be shortened because of bank collapsing and adding to the rapid silting of the reservoir. Slope failures endanger the operation of the control structures of hydroelectric schemes and make difficult water management. Sometimes, landsliding on reservoir shores leads to catastrophic damages (Kiersch, 1964).

Topography is one of the main factors of landslide formation, and one of the landslide indicators (Emelyanova, 1972; Záruba and Mencl, 1982). Therefore, digital terrain modelling is widely used in techniques to recognise, analyse, and assess slope instability risk (Guzzetti et al., 1999; Montgomery et al., 2000; Fernandes et al., 2004). These methods are based on integrating data of geomorphometry (slope gradient, aspect, and shape), geology (spatial distribution of ‘critical’ sediments), meteorology (precipitation amounts), and hydrology (groundwater regime). A slope is commonly recognised as instable if its steepness is more than 15° (Emelyanova, 1972). Landslides usually occur in relative accumulation zones, all other factors being equal (Lanyon and Hall, 1983). This is because convex-convex form of slopes provides sufficient moistening of soils and sediments there. There are various engineering, geomorphic, and mathematical methods to reveal, evaluate, and predict landsliding on reservoir shores (Minervina and Khositashvili, 1974; Finarov, 1986). Maps of relative accumulation zones have not been used for this purpose.

To exemplify a basic principle of application of maps of relative accumulation zones, we consider a mountainous area with a large depression. The area size is about 4 by 4 km. A square-gridded DEM of the study area has a mesh size of 10 m (Fig. 2a). A reservoir is under construction in the depression. After reservoir filling, the maximal water level will be 1343 m. It is desired to find potentially instable sites on the depression slopes, which may be activated by the reservoir filling and operation.

To reduce a high-frequency noise, we applied three iterations of smoothing to the DEM using 3×3 kernel with linear inverse distance weights. Digital models of slope steepness (Fig. 2b), horizontal curvature (Fig. 2c), and vertical curvature (Fig. 2d) were derived from the smoothed DEM by the method of Evans (1980). Models have a resolution of 10 m. A map of relative accumulation zones (Fig. 2e) was obtained using k_v и k_h models.

Areas marked by $G > 15°$ are typical for the western and northeastern slopes of the depression as well as for ridges in the southeastern corner of the study area (Fig. 2b). However, there is a terrace about 500 m wide between the reservoir and the northeastern and northwestern slopes, and one of the southeastern ridges. Therefore, it is unlikely that landsliding on these slopes may be connected with the reservoir operation. We can also eliminate a slope in the northwestern corner of the study area from the further consideration: the slope belongs to an adjacent catchment. Hereafter, our main concern is the southwestern slope of the depression and the scarp along the northeastern reservoir shore marked by the narrow and long stripe of values $G > 15°$ (Fig. 2b).

Let us delineate areas marked by $G > 15°$ within relative accumulation zones, which are (a) adjacent to, upslope the maximal water level (1343 m), and (b) situated on the southwestern slope. Relying on the map obtained (Fig. 2f), we can conclude that the southwestern slope of the depression is characterised by the highest landslide hazard. This is because many potentially instable sites are located there one above the other. This configuration may lead to the ‘domino effect’, when a movement of the masses in one site may trigger movements throughout the slope. On other reservoir shores, areas of potential slope instability are, more or less, evenly distributed along the terrace scarp. To adjust the map obtained and to range revealed areas according to the instability level, one can use data on soils, sediments, plant cover, and groundwater.

PREDICTION OF SOIL DEGRADATION AND CONTAMINATION ALONG PIPELINES

Petroleum and gas pipelines have an adverse effect on soils. First, in a pipeline installation, an area of the disturbed soil cover may range from 400 to 1000 ha per 100 km of a pipeline route (Geltser and Geltser, 1994). As a result, technogenic soils are formed. They are marked by degraded physical, chemical, and biological properties (Naeth et al., 1988; Burgess and Harry, 1990; Geltser and Geltser, 1994). Second, pipeline damage may lead to an outflow of oil and petroleum products. Their flowing and concentration in local depressions result in soil contamination and destruction of the plant cover, while the further infiltration leads to groundwater deterioration (Eiceman et al. 1985; Couillard, 1986). Third, a pipeline can play a role of a geochemical barrier. Underground and elevated pipeline sections are usually constructed to pass gullies, intermittent and ephemeral streams. Nevertheless, pipeline elements can retard overland and intrasoil lateral flows of water and solved or suspended substances drained by natural channels (Crampton, 1988; Naeth et al., 1988; Burgess and Harry, 1990). This can lead to changes in water and salt regimes, waterlogging, and salinisation of lands on adjacent territories. These processes may influence a pipeline insulation and cause corrosive failures, in addition to the general degradation of a landscape.

Environmental monitoring of pipeline corridors is usually carried out using remotely sensed data (Jadkowski et al., 1994; Um and Wright, 1996; Gauthier et al., 2001). Some approaches of digital terrain modelling, such as derivation of slope steepness and curvatures, are used in pipeline routing (Feldman et al., 1995; Rylsky, 2004). Up to now, maps of relative accumulation zones have not been used to predict soil degradation and contamination along pipelines.

To exemplify a basic principle of application of maps of relative accumulation zones, we consider a terrain with a gentle topography. The area size is about 600 by 500 m. A square-gridded DEM of the area has a mesh size of 1.5 m (Fig. 3a). A petroleum pipeline crosses the area. Assume that there is a single failure of the pipeline. The challenge is to predict a migration way of petroleum flowing from the hole, and areas of petroleum concentration. In addition, there is a need to find sites where soil degradation is feasible due to action of the pipeline as a barrier for natural flows.

To reduce a high-frequency noise, we applied three iterations of smoothing to the DEM using 3×3 kernel with linear inverse distance weights. A digital model of specific catchment area (Fig. 3b) was derived from the smoothed DEM by the method of Martz and de Jong (1988). Models of horizontal curvature (Fig. 3c) and vertical curvature (Fig. 3d) were derived from the smoothed DEM by the method of Evans (1980). Models have a resolution of 1.5 m. A map of relative accumulation zones (Fig. 3e) was produced using k_v и k_h models.

A thalweg network is delineated on the map of catchment area (Fig. 3b). This map can be used to determine paths of lateral migration of petroleum (Fig. 3f). Petroleum will concentrate in accumulation zones situated along a flow line originating at the point of the pipeline hole (Fig. 3f). The migration distance of petroleum depends on several factors, such as the volume of petroleum leaking out the pipeline, velocity of this leakage, velocity of the petroleum flow on the land surface, properties of the soil and vegetation covers, etc. This information should be used to refine the map obtained, and to estimate the dynamics of soil contamination.

Soil degradation (waterlogging and salinisation) may occur in relative accumulation zones adjacent to, upslope the pipeline (Fig. 3f). Indeed, local geometry of the relief forms natural conditions for increased moistening of the soil profile and salt concentration in relative accumulation zones (Pennock et al., 1987; Florinsky, 2000; Florinsky et al., 2000; Florinsky et al., 2002). Constructive elements of a pipeline, situated adjacent to, downslope a relative accumulation zone, may form a barrier for overland and intrasoil flows intensifying natural processes of moistening or salinisation. Salinisation may prevail in relative accumulation zones if soils and/or groundwaters contain water-soluble salts. Arid and semiarid climatic conditions can favour soil salinisation. Waterlogging is more probable if the environment is free of water-soluble salts. To estimate dynamics, manifestation, and direction of soil degradation, one should use data on physical and chemical properties of soils as well as regime and chemical content of groundwaters.

COMMENTS

Maps of relative accumulation zones cannot replace existed geological methods. The principles described can serve as additional computerised tool.

Appropriate resolution of a DEM is determined by typical sizes of the object under study. In the search of placers and instable slopes, the typical size is the minimal width of a placer or landslide in the given natural conditions. For each particular study, this parameter may be considered as constant if the study is carried out within a territory with homogeneous topography. In the pipeline monitoring, different portions of a pipeline may require DEMs with different resolution. This is because relief type and typical sizes of landforms can alter along the pipeline route.

All calculations and mapping were done with LandLord 4.0 (Florinsky et al., 1995).

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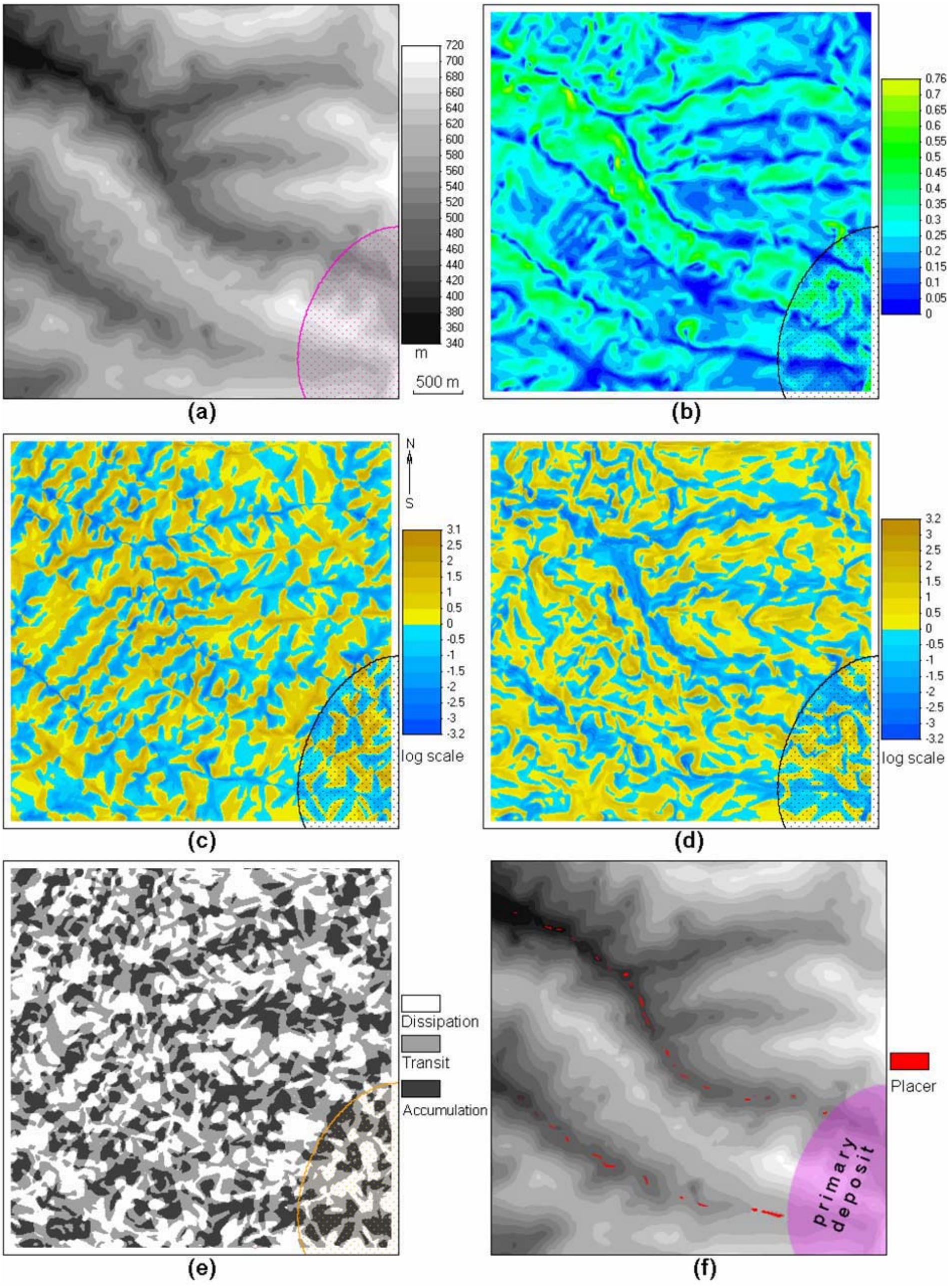

Fig. 1. Exploration of alluvial placers: (a) elevation, (b) slope factor, (c) horizontal curvature, (d) vertical curvature, (e) relative accumulation, transit, and dissipation zones, and (f) the most prospective areas. The primary deposit is hatched.

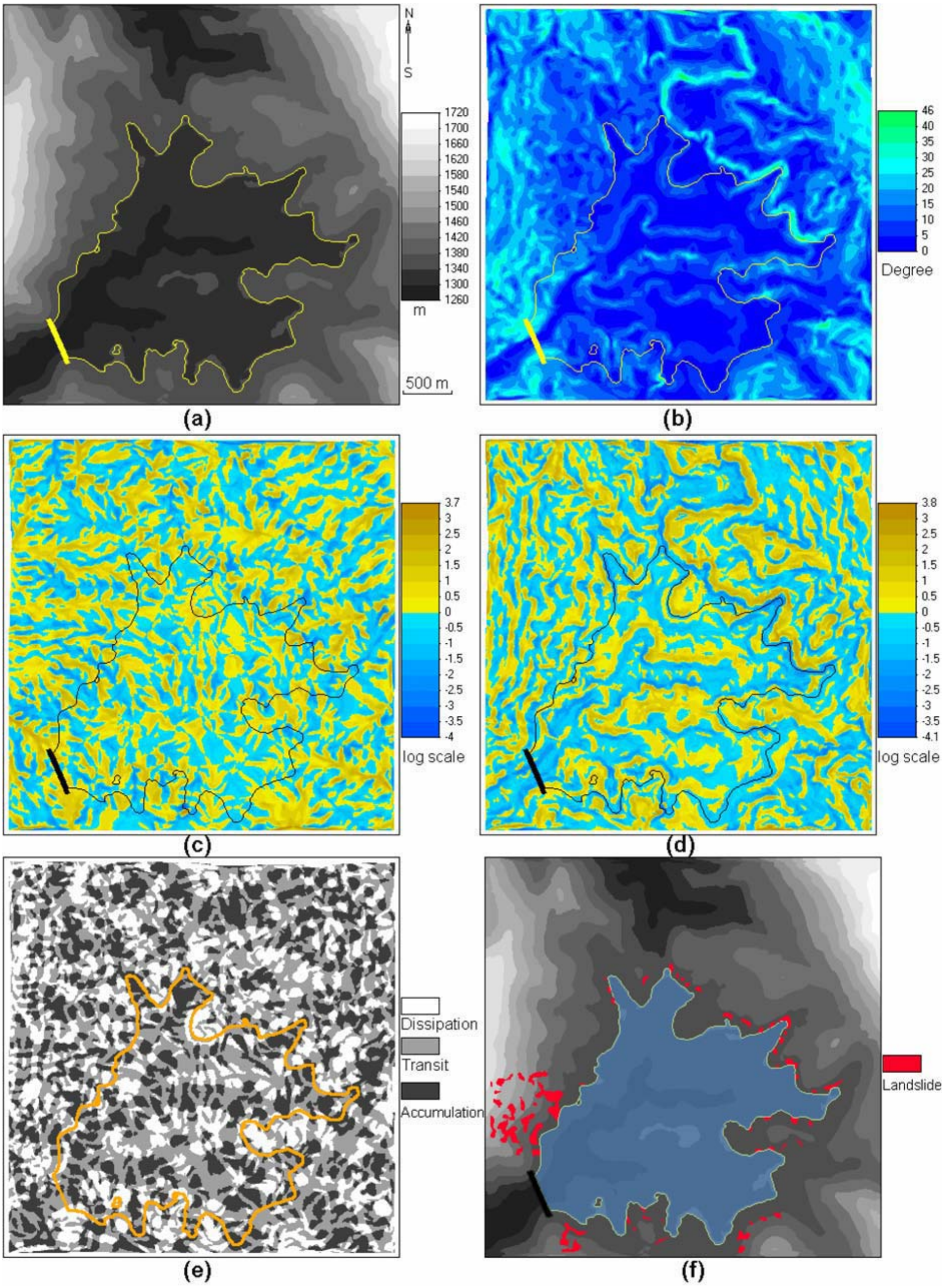

Fig. 2. Prediction of slope instability on reservoir shores: (a) elevation, (b) slope steepness, (c) horizontal curvature, (d) vertical curvature, (e) relative accumulation, transit, and dissipation zones, and (f) areas of possible slope instability. The dam and the maximal water level (1343 m) are delineated.

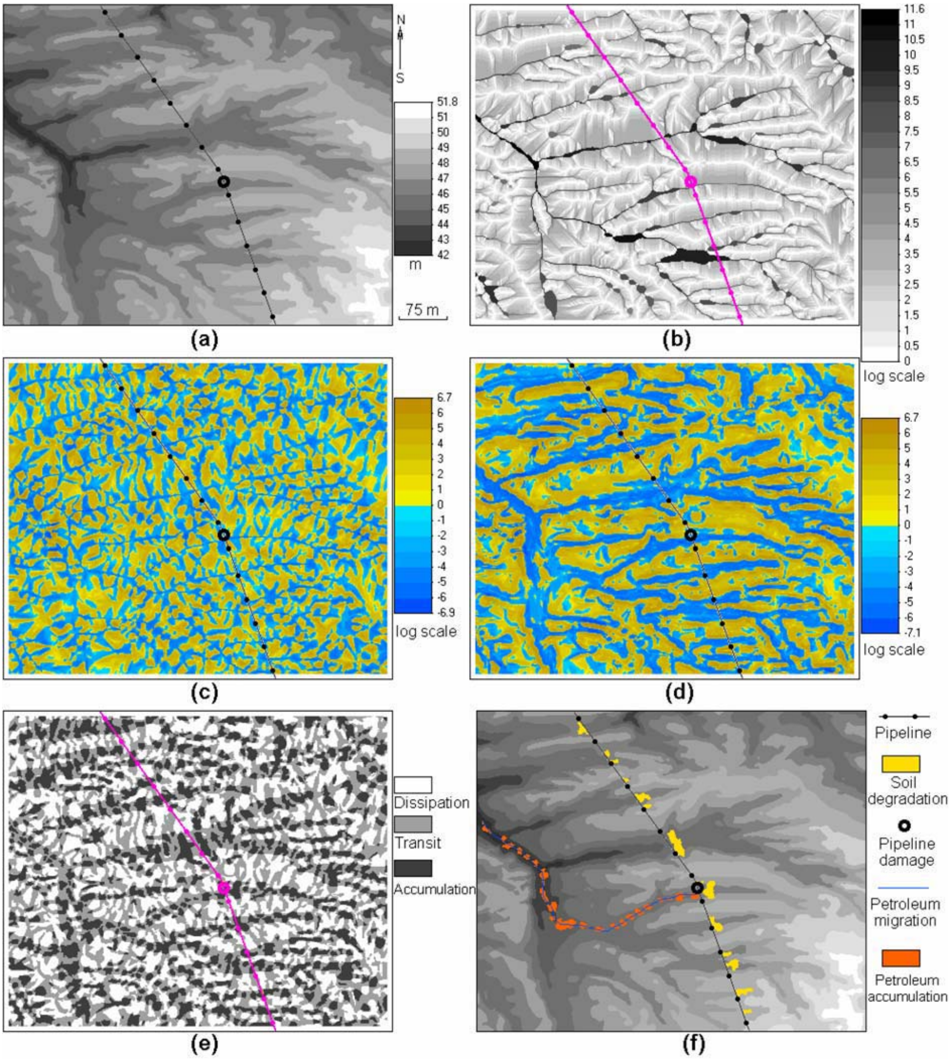

Fig. 3. Prediction of soil degradation and contamination along the pipeline: (a) elevation, (b) specific catchment area, (c) horizontal curvature, (d) vertical curvature, (e) relative accumulation, transit, and dissipation zones, and (f) areas of possible degradation and contamination of soil cover.