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Hydrologic Modeling Impacts of Post-mining Land Use Changes on Streamflow of Peace River, Florida

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Abstract: Whether mining activity results in reduced flow of surface water in the Peace River Watershed of Florida has been the subject of much debate. With increased dependence of downstream users on surface water flow of the Peace River as a source of drinking water for four coastal counties in Southwest Florida and problems of water security, the debate has been intensified. It is possible to assess relationships of mining with streamflow in the upper reaches of the Peace River Basin using hydrologic modeling and identify mined sub-basins. In this work, land-use change impacts were simulated by the Hydrological Simulation Program—Fortran (HSPF) model based on geographical information system (GIS) tools, to compare pre- and post-mining streamflows at a study site of the Peace River in west-central Florida. The purpose of this study was to determine if land-use changes caused by mining have negatively impacted streamflow in the Peace River. Changes of land use were identified before and after mining activities. A coupled volume-water depth-discharge (*V*-*h*-*Q*) model based on stage/storage and stage/discharge was applied using HSPF for the pre-mining and post-mining models, respectively. Daily simulated post-mining hydrographs from HSPF were plotted with the calibrated pre-mining results and streamflow hydrographs from the 18 gauging stations, to compare timing of peaks, low flows and flow trends. Analyses of percent exceedances of flow frequency curves of the streams indicated that most streams had similar distributions for mined (reclaimed) and pre-mining periods. In the streamflow change analysis, streamflows actually increased in mining-affected basins at nearly half the stations. Streamflows at other stations diminished. Overall from this comprehensive study, there were declines in streamflow at most gauging stations on the mainstem of the Peace River and its tributaries. The results of this study suggest that regional planning is urgently needed to propose reclamation schemes that enhance regional hydrology.

Keywords: post-mining; land-use changes; streamflow; hydrologic model; Hydrological Simulation Program—Fortran (HSPF) model

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1 Introduction

Significant declines in streamflow have been documented for gauging stations on the mainstream of the Peace River in Florida, U.S.A., with the highest rates of decline observed in the upper reaches of the river near Bartow and Zolfo Springs. It has been reported that long-term rainfall deficits have played a major role in the reduced flows, but human factors (e.g., mining and irrigation) have also been important (Green *et al.*, 1995; Scott, 1998; Flannery *et al.*, 2002; Brown, 2005). The hydrologic environments of the upper Peace River Basin have been substantially altered by extensive phosphate mining. It is possible to assess relationships of this mining with streamflow in the upper basin and identify mined sub-basins (Carlson and Arthur, 2000; Antwi *et al.*, 2008). A comprehensive comparison of the effects of pre- and post-mining on flows in the Peace River is urgently

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required. This assessment should be multifaceted for surface water drainage and surface water/groundwater relationships which caused by mining (SWFWMD, 2001).

Whether phosphate-mining activity has reduced the flow of surface water in the Peace River watershed has been the subject of much debate. With increased dependence of downstream users on surface water flow of the river as a source of drinking water for four coastal counties in Southwest Florida, the debate has been intensified. Some researchers have found that streamflows in basins with mining were equal to or higher than those in basins without mining (Schreuder *et al.*, 2006; Kelly and Gore, 2008). They attributed this to more available water because of reduced evapotranspiration (ET) in mined or reclaimed areas (Schreuder *et al.*, 2006). Kelly and Gore (2008) presented a five-year running average streamflow of the Peace River at Arcadia, the Withlacoochee River at Holder, and the Alafia River at Lithia. His results showed similar patterns and were therefore used to emphasize that there was essentially no discharge difference between the three watersheds. Other study like the Southwest Florida Water Management District (SWFWMD, 2001) compared the hydrology of the three major river basins to address an assertion that certain land uses such as phosphate mining have been the main cause of decline in surface water flow of the Peace and Alafia rivers (Schreuder *et al.*, 2006).

Other studies detected or quantified changes for land-cover (mining) impacts on streamflow (Siriwardena *et al.*, 2006; Lazareva and Pichler, 2007; Seibert and McDonnell, 2010). It is rare by using hydrologic models to discern mining impact change. Hydrologic Simulation Program—Fortran (HSPF) is a comprehensive surface water simulation model frequently applied to the modeling of rainfall-runoff relationships (Bicknell *et al.*, 2001). In recent years, many applications of HSPF have been reported in the literature (Iskra and Droste, 2007; Lian *et al.*, 2010; Jeon *et al.*, 2011; Diaz-Ramirez *et al.*, 2012; Xie and Lian, 2013). This model describes volume-dependent discharge of a stream based on stage, surface area, volume, and discharge entries in a function table (FTABLE). In the present work, land-use change impacts are simulated by HSPF based on GIS tools. This approach is used to quantify the changes in land use for comparing streamflows of pre-mining and post-mining conditions at a study site of the Peace River in Southwest Florida, U.S.A.

Within the upper Peace River Basin (upstream of Bowling Green), many of the natural drainage system characteristics have been altered by phosphate surface mining (Lewelling *et al.*, 1998). In the study area, phosphate mining methods are mostly surface-based, and surface mining methods have very different effects on hydrology. Some examples are like increased water yield because of increased impervious surfaces, decreased transpiration, variation of runoff timing caused by changes of drainage density.

Given the above, the specific hypothesis of this study was proposed, i.e., does phosphate mining reduce or increase streamflow in the Peace River Basin? Our objective was to analyze whether streamflow increases, decreases, or remains unchanged at all gauging stations after mining activities that altered land use in the study area. We carried out as follows to accomplish this objective: 1) changes of land use were identified before and after mining activities; 2) a coupled volume-water depth-discharge (V-h-Q) model based on stage/storage and stage/discharge was applied using HSPF for the pre-mining and post-mining models, respectively; 3) daily simulated post-mining hydrographs from HSPF were plotted with the calibrated pre-mining results and streamflow hydrographs from 18 gauging stations to compare timing of peaks, low flows and flow trends. Comparisons of pre-mining and post-mining cumulative frequency distributions (flow duration curves) are made to assess whether those distributions were different at a selected significance level.

2 Materials and Methods

2.1 Study area

The Peace River Basin is in Southwest Florida with an area of 932 km^2. It is characteristic of coastal plain environments with a high drainage density made up of many creeks and rivers (e.g., Bowlegs, Whidden, Little Payne, Little Charlotte, Payne Creek) which are connected to the Peace River (Fig. 1). Mining was mainly in the southeast part of the study area; hence a 69 km^2 area was selected. Land use types include water, range land, forest, agricultural land, urban land, mining land, irrigated crops, irrigated trees, and high slope grass. Compared with pre-mining environments, these land use types have been dramatically modified by phosphate mining.

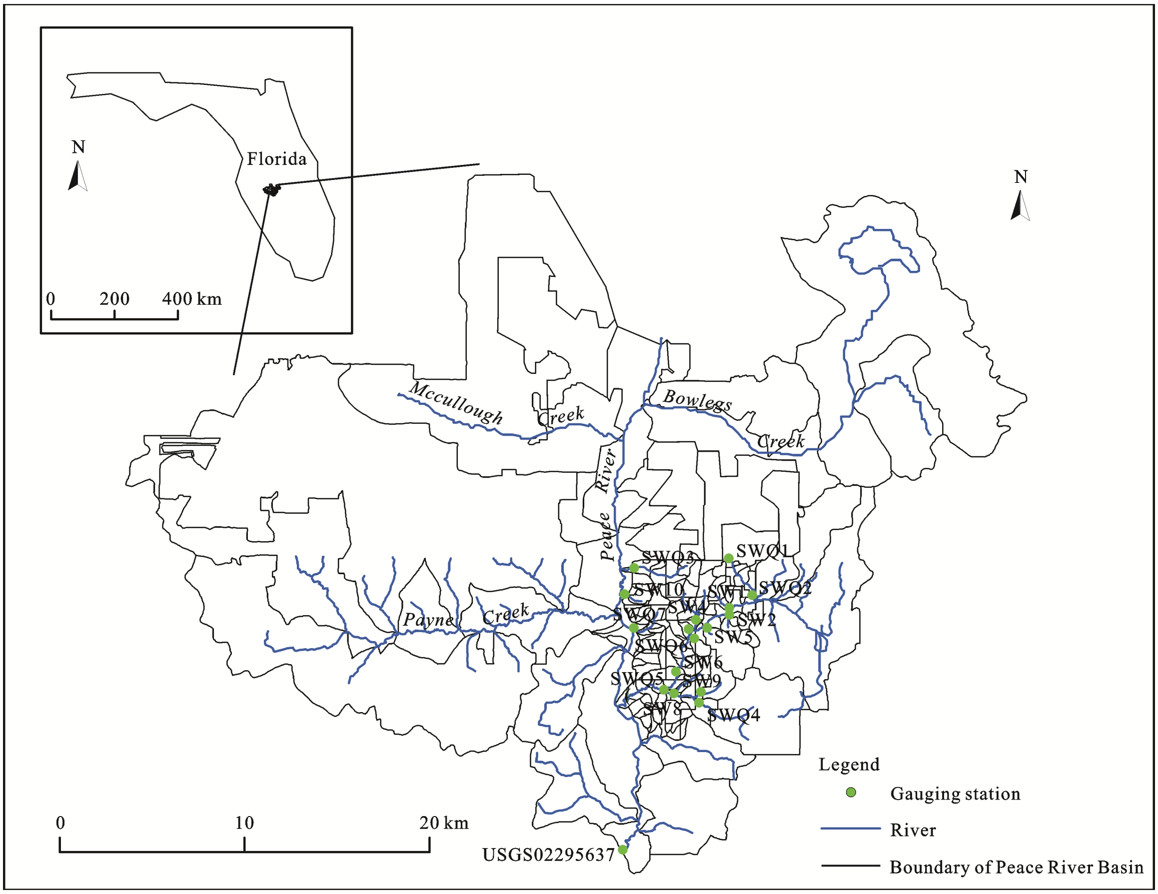

Fig. 1 Location of study area and gauging stations

At a minimum, HSPF requires precipitation and ET time series inputs to simulate hydrographs. Observed flow is also necessary as a basis for calibration. Within the mining area, there were 18 gauging stations (Fig. 1), with daily flow and stage records used as the observed data. Observed flow rate data were completed for all stations during June 1, 2004–July 25, 2005. Meteorological data for HSPF included hourly precipitation and computed time series of potential ET. Precipitation data were obtained from Bowling Green station and ET data from Fort Green Mine, Wachula, and U.S. Geological Survey (USGS) stations. Discharge of the Peace River was measured by the USGS station at Zolfo Springs (Fig. 1).

2.2 Coupled *V*-*h*-*Q* model

Traditional calibration using general stream cross sections (e.g., Manning-based) and/or other discharge relationships (Atabay and Knight, 1999; Dawdy *et al.*, 2000) can be time-consuming and uncertain, owing to limited calibration stations and potentially unreasonable assumptions. The relationship between discharge (Q), volume (V), and water depth (h) must often be estimated because of a lack of detailed survey data. Area-depth and volume-depth relationships are usually determined from detailed surveys and/or bathymetric maps that are costly and labor-intensive to produce, and specific to each depression. Stage/storage/discharge relationships are basic and essential steps for the hydraulic setup of a model, e.g., FTABLE of HSPF.

There have been recent insights about coupled generalized stage/storage and stage/discharge relationships to set up FTABLEs in HSPF, using the data of 18 gauging stations (Zhang *et al.*, 2009). The coupled *V*-*h*-*Q* model based on stage/storage and stage/discharge was applied at the study area, using HSPF for the pre-mining model (Zhang *et al.*, 2009). Equations for calculating the main FTABLE variables are listed in Table 1.

2.3 Model calibration and validation

In a previous study, Zhang *et al.* (2009) carried out model calibration, validation and sensitivity analysis for

Table 1 Variables of FTABLE generation for coupled *V-h-Q* model

FTABLE variable	Calculation equation	Explanation
Volume	If depth (d) was higher than root zone depth: $V = V_{FS} + \left(\frac{d - d_{RZ}}{d_{Full} - d_{RZ}}\right)^{V_f} \times A_w \times \left(\frac{d_{Full} - d_{RZ}}{V_f}\right)$ Otherwise: $V = \frac{d}{d_{RZ}} \times V_{FS}$	V: volume (storage) (L^3); d: depth (L); d_{RZ}: depth of root zone (L); d_{Full}: bank full depth (L); V_{FS}: volume of full soil (L^3); A_w: wetland area (L^2); V_f: volume factor
Discharge	$Q = Q_{10} \times \left(\frac{d - d_{Invert}}{d_{10} - d_{Invert}}\right)^{Q_f}$	Q: discharge (L^3/T); Q_{10}: 10% exceedence discharge threshold (L^3/T); d_{10}: water depth corresponding to the 10% discharge exceedence (L); d_{Invert}: inverted water depth (L)

the study area. The model was calibrated and validated using 18 available flow gauges for pre-mining. Then, the validated parameters were used for the post-mining condition. Calibration comparisons were made with cumulative and daily rate hydrographs, flow-exceedance curves and model versus observation scatter plots. Calibration results compared reasonably well to observed daily flow rates, daily stages, and flow durations. The simulated results indicated that the coupled *V-h-Q* model was capable of reasonable predictions of actual volume-stage-discharge behavior in wetlands. Additionally, the statistical analysis indicated adequate agreement between the simulated results and observed data. The modeling results of predicted daily streamflow correlated reasonably well with measured streamflow. Details of the calibration process are described in Zhang *et al.* (2009).

The predictive ability of the model and calibration efficiency were improved by systematic calibration using the coupled *V-h-Q* model, as opposed to traditional parameter manipulation. Constraints added by the coupled model reduced uncertainty at stations where calibration data were unavailable. The Nash-Sutcliffe efficiency (NSE) and correlation coefficient computed using observed and simulated daily flows were 0.90 and 0.96 at the Peace River, with error −3.97%, and there were satisfactory simulation results at other stations in the model domain. Throughout the calibration period, the calibration results were considered reasonable estimates of streamflow at most of the 18 gauging stations.

During post-mining model setup, the calibrated parameters were directly applied in the model. Land use was categorized into nine types, as for pre-mining. The boundaries of post-mining sub-basins were adjusted upon the reclamation program. A surface water model (HSPF) was constructed for the surface water domain, similar to pre-mining, and the model was revised for land use and basin change in the mined area which is north of a recently delineated South Fort Meade extension. The FTABLE was constructed according to the coupled *V-h-Q* model, based on stage/storage and stage/discharge relationships for post-mining conditions. The output with streamflow at each station of the post-mining model was compared with that of pre-mining model to analyze any streamflow change at all stations, after mining activities altered land use in the study area.

3 Results and Discussion

3.1 Land-use distribution and change

Change detection is the process of identifying change of land use before and after mining activity. The land-use distribution and changes from pre-mining to post-mining in the study area are shown in Table 2. Changes from one land-use type to another were detected by constructing a land-use change table with characterizations of ′negative change′, ′no change′ and ′positive change′. Negative change means land-use area reduction; positive change, increase; and no change, a constant area. All changes were calculated in an ArcGIS environment.

The same land-use type was assessed for pre-mining and post-mining. The total area of post-mining is slightly higher than that of pre-mining, owing to the reclamation program extending to the northeast part of the study area. The results were unaffected by the difference in total area, because the difference over the entire area was negligible.

The results of Table 2 show that the distribution of land use types for pre-mining was in the following de

Table 2 Land-use changes for pre-mining and post-mining

Land use type	Pre-mining		Post-mining		Change (ha)	Change (%)
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)		
Water	703.2	10.2	876.3	12.7	173.1	24.6
Range land	2164.4	31.2	2111.6	30.5	–52.8	–2.4
Forest	459.2	6.6	682.2	9.9	223.0	48.6
Agricultural land	18.5	0.3	18.5	0.3	0.0	0.0
Urban land	245.9	3.5	215.2	3.1	–30.7	–12.5
Mining land	2.7	0.04	243.9	3.5	241.2	–97.6
Irrigated crops	266.0	3.8	29.7	0.4	–236.3	–88.8
Irrigated trees	1224.9	17.7	681.5	9.8	–543.4	–44.1
High slope grass	1501.6	21.7	1727.5	24.9	225.9	24.9
Total	6586.4	100.0	6587.5	100.0	1.1	0.016

scending order: range land (31.2%), high slope grass (21.7%), irrigated trees (17.7%), water (10.2%), forest (6.6%), mining land (0.04%), irrigated crops (3.8%), urban land (3.5%), and agricultural land (0.3%). For post-mining the order was: range land (30.5%), high slope grass (24.9%), water (12.7%), forest (9.9%), irrigated trees (9.8%), mining land (3.5%), urban land (3.1%), irrigated crops (0.4%), and agricultural land (0.3%). Areas of positive change (increase) during post-mining relative to pre-mining were from high to low: mining land (241.2 ha), high slope grass (225.9 ha), forest (223.0 ha), and water (173.1 ha). The negative change ranking was irrigated trees (−543.4 ha), irrigated crops (−236.3 ha), range land (−52.8 ha), and urban land (−30.7 ha). Almost all of the agricultural land classification maintained its cover, with no change to other land-use types.

Mining increased about 90 times over its original coverage area during pre-mining (from 2.7 ha to 243.9 ha). High slope grass cover increased 24.9%. These gains were largely taken from range land and irrigated trees, particularly in the north central part of the study area. The area of irrigated crops declined drastically over the study period by 236.3 ha, which represents an 88.8% decrease in the northeast of the study area. A detailed look at the changes shows that most of this lost area was converted into range land and high slope grass; other conversions were distributed across the other land-use types.

During pre-mining, 17.7% of the area was covered with irrigated trees. Post-mining, however, percent of the area of these trees decreased to 9.8%. This indicates that the area of irrigated trees classification decreased, with a −44.1% change of its original area (Table 2). Meanwhile, the area of water increased by 24.6% relative to pre-mining, and parts of the range land areas were converted to water.

3.2 Streamflow change

Simulated post-mining daily hydrographs from the HSPF were plotted with the calibrated pre-mining results and streamflow hydrographs from the 18 gauging stations, to compare timing of peaks, low flows and flow trends (Figs. 2–4). These figures also compare pre-mining and post-mining cumulative frequency distributions (flow duration curves), to assess whether those distributions were different at a selected significance level.

A flow duration curve characterizes the ability of a basin to produce flows of various magnitudes. The shape of this curve in its upper and lower portions is particularly significant in evaluating extremes of stream and basin behavior. Percent exceedance is the percentage of time that streamflow volume equals or exceeds a certain value; that is, *P*-90 means that 90% of the time, streamflow meets or exceeds a given value, and 10% of the time it is less than that value. The *P*-10 value is generally associated with flow in surface water streams during flood conditions. Similarly, *P*-50 flows are associated with average streamflow, while *P*-90 generally represents baseflow conditions. The results of Figs. 2–4 show that at one-third of the 18 gauging stations, the streamflow met the value almost 100% of the time. These gauging stations are USGS 02295637, SWQ5, SW4, SW6, SW9 and SWQ6, most of which are in downstream locations. Five gauging stations (SWQ2, SWQ4, SW7, SW10, and SW5) had 90% of baseflow conditions. Other stations were near or less than 50% exceedance, mostly in upstream locations.

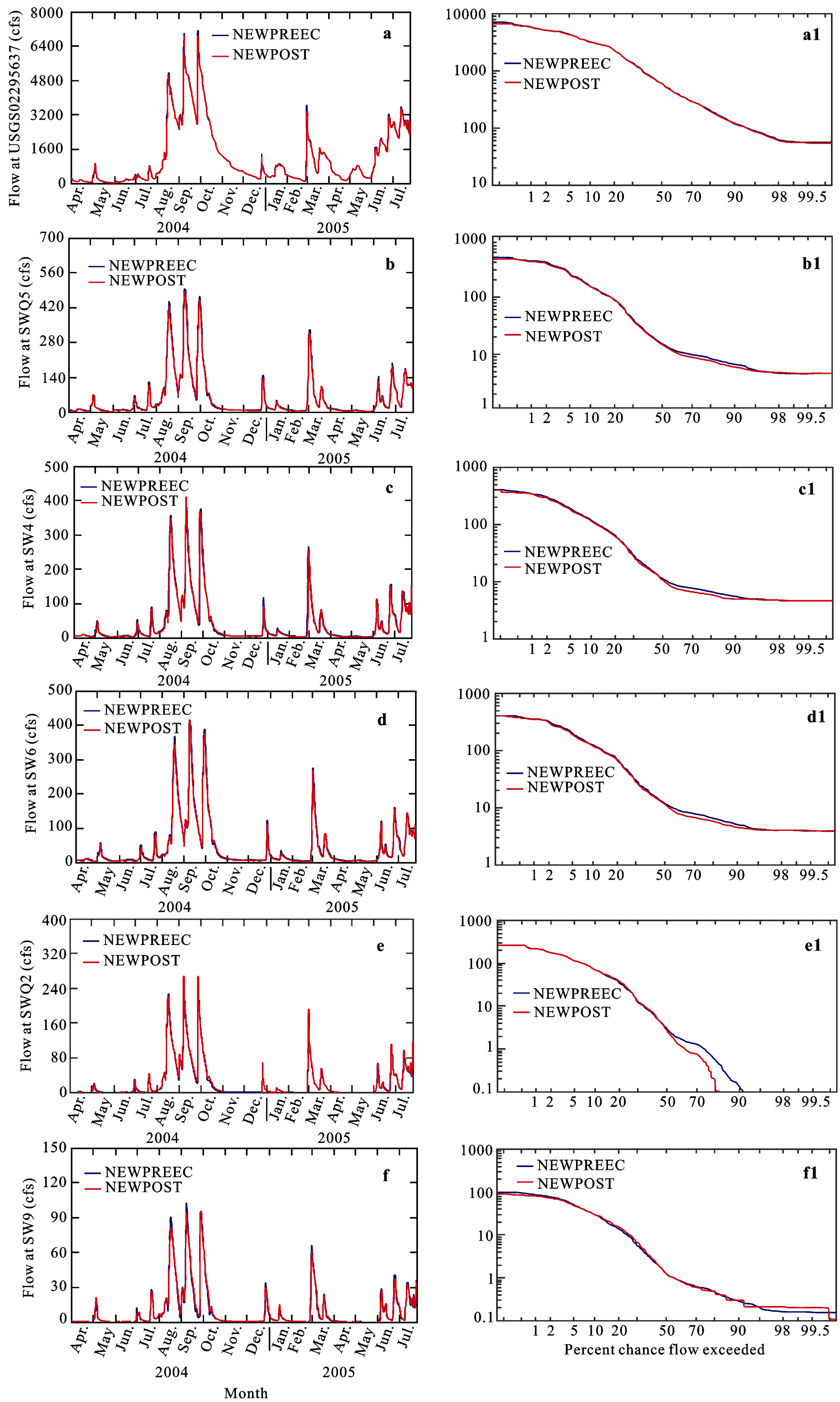

Fig. 2 Simulated pre-mining (NEWPREEC) versus post-mining (NEWPOST) daily streamflows. a, USGS02295637; b, SWQ5; c, SW4; d, SW6; e, SWQ2; f, SW9; a1–f1 are corresponding flow duration curves at each station

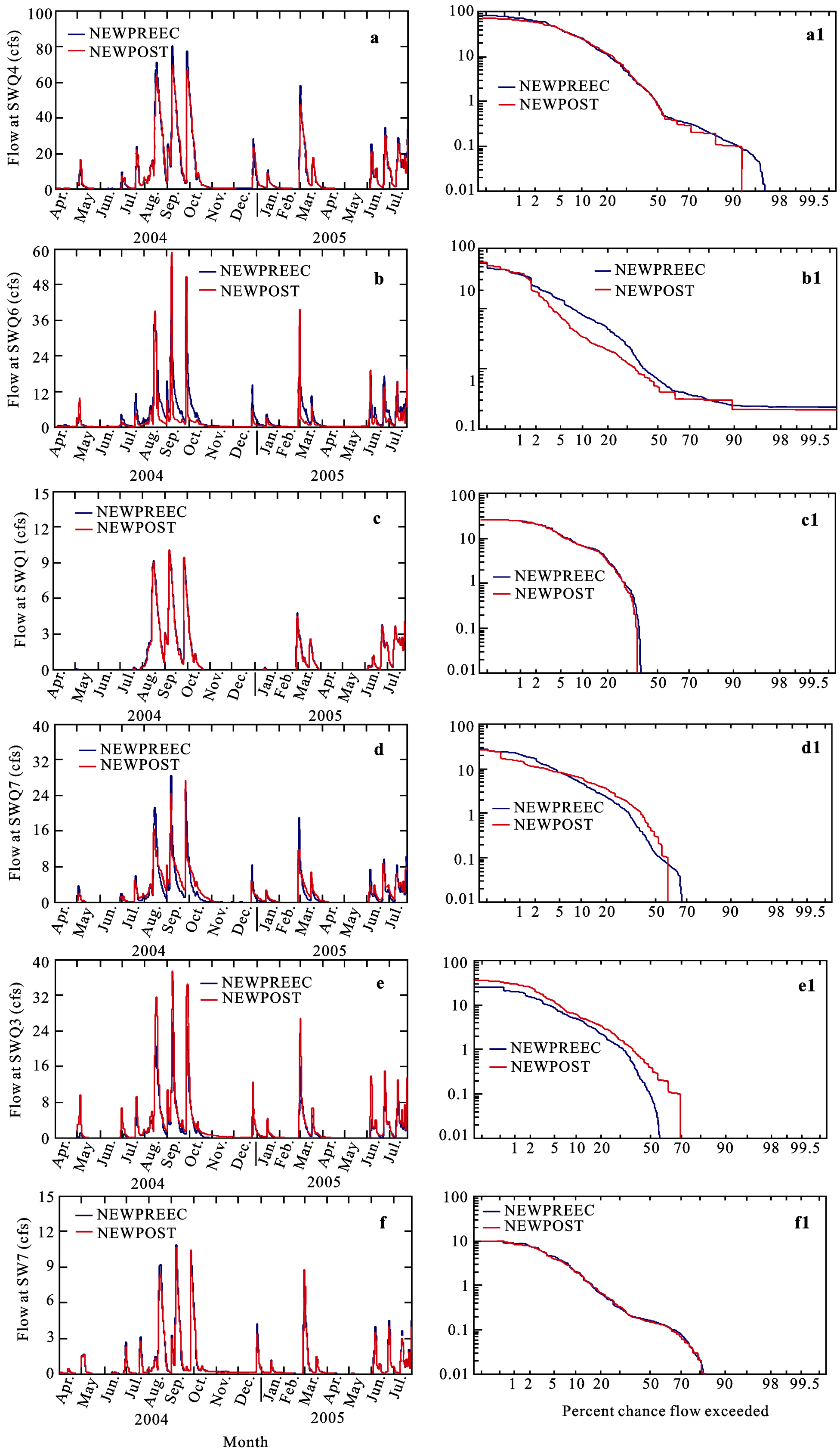

Fig. 3 Simulated pre-mining (NEWPREEC) versus post-mining (NEWPOST) daily streamflows. a, SWQ4; b, SWQ6; c, SWQ1; d, SWQ7; e, SWQ3; f, SW7; a1–f1 are corresponding flow duration curves at each station

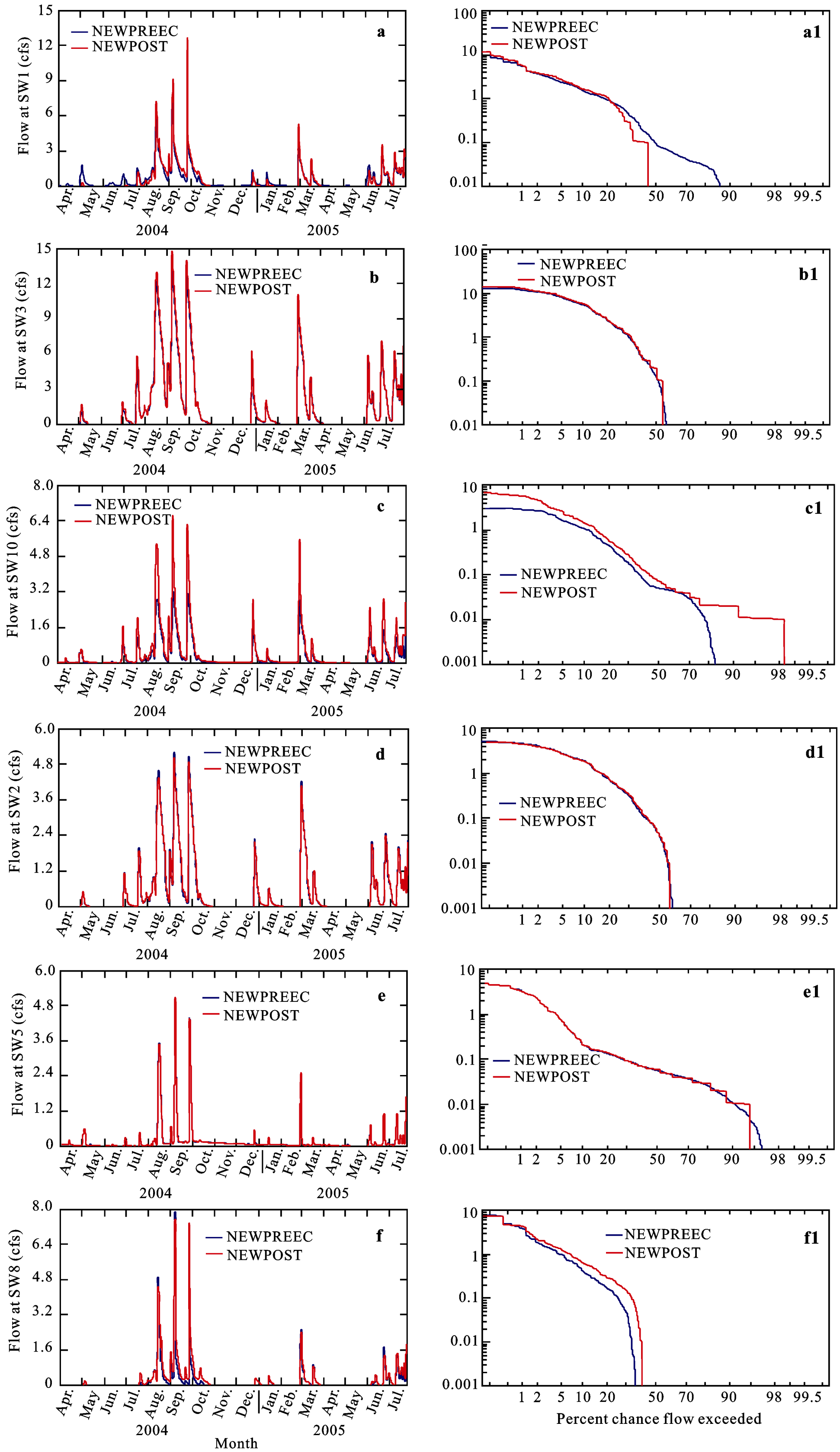

Fig. 4 Simulated pre-mining (NEWPREEC) versus post-mining (NEWPOST) daily streamflows. a, SW1; b, SW3; c, SW10; d, SW2; e, SW5; f, SW8; a1–f1 are corresponding flow duration curves at each station

Pre-mining and post-mining hydrograph comparison statistics were derived, including percent of change, which was calculated by subtraction of post-mining and pre-mining divided by pre-mining (Table 3). These were used to evaluate change rates for model performance and showed whether streamflow decreased at each station. This represents a very sensitive approach to accurately determine if and to what extent land-use changes affected streamflow.

Noting that in Table 3 for all the stations, streamflows at SW2 and SW9 remained almost the same after mining activities, because land use types and contributing areas were unchanged. At nearly half the stations, streamflows actually increased in mining-affected basins. Streamflow at SW8 increased 30.3% over pre-mining; other increases were SW10 at 52.1%, SWQ3 at 41.9%, SWQ7 at 11.0%, SW3 at 4.0%, SWQ2 at 0.9%, and SW1 at 0.3%. Streamflows also increased in some non-mined sub-basins, but this was due to import of groundwater pumped from underlying confined aquifers for irrigating agricultural fields. Overall, it is clear from the findings that phosphate mining and subsequent reclamation did not reduce surface water flows in the affected sub-basins.

In contrast, streamflows at the other ten stations diminished somewhat. This was especially so at SWQ6, where streamflow decreased 36.2%. Figure 5 reveals that the land use types mainly changed from irrigated trees to high slope grass and range land. Flow routing in the reaches also changed (pre-mining reach and post-mining reach) in the figure). These findings indicate that if significant areas are converted from irrigated trees to range land or grass by reclamation programs, streamflow could decrease because of increased ET and altered routing. The remaining eight stations had less than 5% decrease of streamflow relative to that of pre-mining. Mining land use increased compared with pre-mining at those gauging stations. The surface discharge of USG02295637 at Zolfo Springs was 576 391 cfs before mining and 571856 cfs afterward, a reduction of 0.8%.

4 Conclusions

In this study, we coupled generalized stage/storage and stage/discharge relationships for constructing FTABLEs in HSPF using 18 gauging stations on the Peace River Basin of Southwest Florida, for pre-mining and post-mining models.

Table 3 Streamflow comparison between pre-mining and post-mining at each station

Station	Contributing area (ha)	Pre-mining total flow (cfs-days)	Post-mining total flow (cfs-days)	Flow change (cfs)	Percent change (%)
SW5	198	84.7	84.7	–0.1	–0.1
SW8	254	94.0	122.5	28.5	30.3
SW10	125	145.9	221.9	76.1	52.1
SW2	410	239.1	239.1	0.0	0.0
SW1	500	262.9	263.7	0.8	0.3
SW7	625	358.8	347.2	–11.6	–3.2
SWQ7	561	797.4	885.1	87.7	11.0
SWQ3	946	804.7	1141.5	336.8	41.9
SW3	1135	721.2	750.1	28.9	4.0
SWQ1	1256	1056.0	1015.0	–41.0	–3.9
SWQ6	1714	1493.6	952.2	–541.4	–36.2
SWQ4	4701	3557.5	3473.6	–83.9	–2.4
SW9	6253	4495.0	4494.9	–0.1	0.0
SWQ2	14605	10822.5	10918.2	95.7	0.9
SW4	19639	19527.9	18796.2	–731.7	–3.7
SW6	21307	20579.4	19762.4	–817.0	–4.0
SWQ5	28548	26284.0	25569.0	–715.0	–2.7
USGS02295637	568285	576391.1	571856.4	–4534.7	–0.8

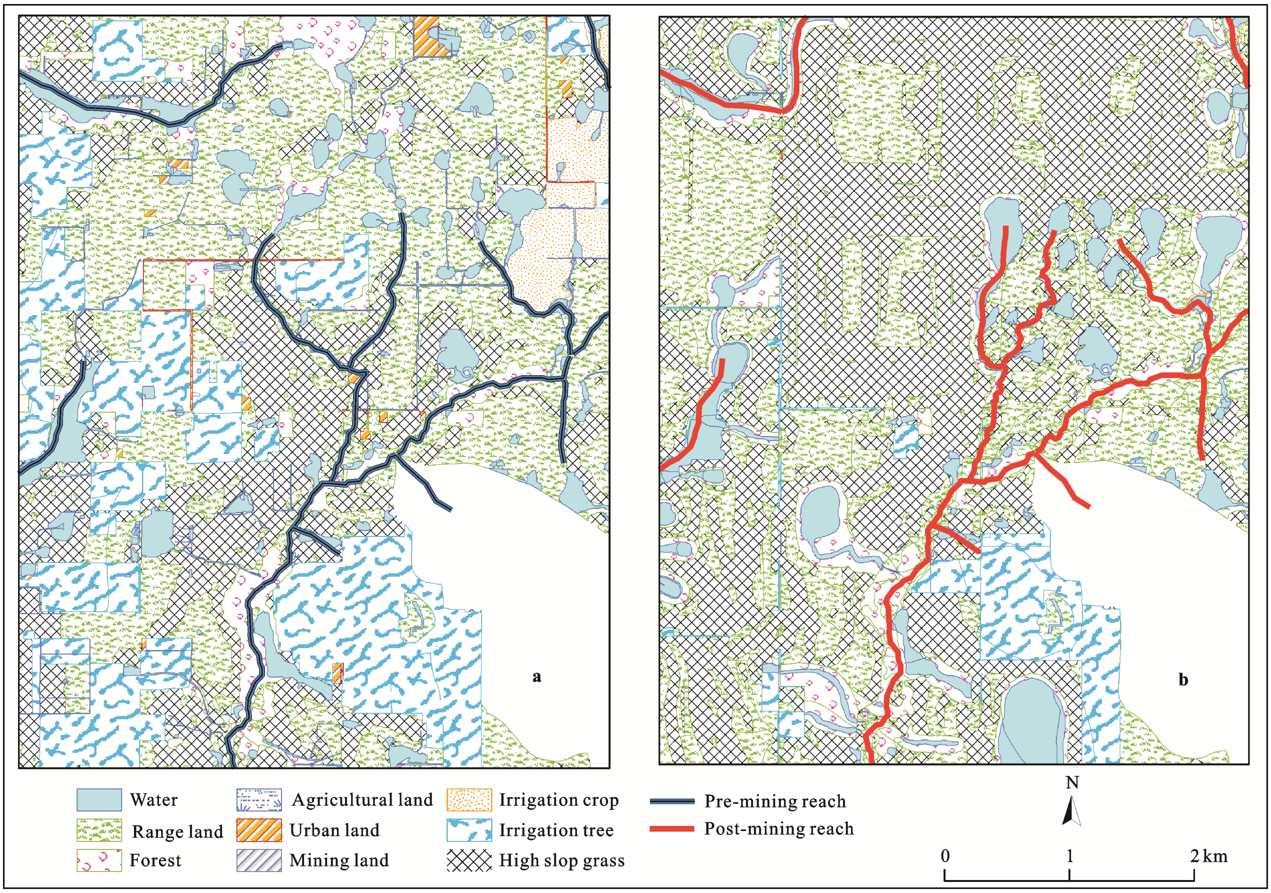

Fig. 5 Land-use changes and routing reach. a, pre-mining; b, post-mining

A land-use change analysis revealed that areas of positive change (increase) during post-mining relative to pre-mining were ordered from high to low as high slope grass (590.2 ha), mining land (241.2 ha), forest (223.5 ha), and water (173.1 ha). The negative change (area decrease) ranking was irrigation tree (−605.4 ha), range land (−352.8 ha), irrigated crop (−236.2 ha), and urban land (−30.7 ha).

From the streamflow and combined land-use change analysis, it is clear that the land-use change altered streamflow. The influences were categorized as follows. 1) No effect: the results showed that streamflow at SW2 and SW9 remains constant after mining. 2) Positive effect: at nearly half the stations (SW8, SW10, SW1, SWQ7, SWQ3, SW3 and SWQ2), streamflows actually increased in mining-affected basins. 3) Negative effect: streamflows at other stations diminished somewhat. In particular, streamflow at SWQ6 decreased dramatically, with 36.2% less than pre-mining conditions. This was attributable to significant areas that were converted from irrigated tree to range land or grass, with increased ET and altered routing. The remaining eight stations had less than 5% streamflow decrease compared with pre-mining. Surface discharge of USG02295637 at Zolfo Springs was reduced by 0.8% after mining. Overall from this comprehensive study, there were some streamflow reductions at gauging stations on the Peace River main-stem, attributable to post-mining land use changes.

Regardless of any streamflow change in the area caused by mining or any other anthropogenic activity, regional planning is needed to better define watershed boundaries and propose reclamation schemes that enhance regional hydrology. The relevant concern is mining effects on regional hydrology. Future research should address larger-scale issues related to adaptively managing the restoration landscape and how it should be hydrologically and ecologically structured, as well as how humans should fit within that organization.

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