The Importance of Fluvial Geomorphic Landform Characteristics to Ensuring Stability Against Erosion and Their Use in Landform Design

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Abstract

The fluvial geomorphic approach to designing landforms that are stable against erosion and promote sustainable land development, requires that essential landform characteristics are incorporated into the landform and that the characteristics are correctly inter-related for proper function. The GeoFluv™ approach to landform design uses measurements of these essential landform characteristics of upland areas and ephemeral, intermittent, and perennial stream channels as input values and integrates them to design a functioning landform. The incorporation of the GeoFluv™ approach into the Natural Regrade computer software greatly simplifies the calculations needed to integrate these input values into a cohesive landform design. As with any computer program, the quality of the input information determines the quality of the output result. This virtual field tour will explore the expression of these GeoFluv™ input values in various locations, discuss their relevance to a stable landform design, and demonstrate how they are used in making a design for a stable landform according to fluvial geomorphic principles.

How Upland Landforms Develop to Maturity

The GeoFluv™ approach to landform design uses an understanding of the fluvial geomorphic processes that work on earth materials over geologic time to shape a stable, mature natural landform to make a design in days to weeks for a reclamation landform that will function similar to the natural, mature landform. The approach recognizes that the *morphology* is related to the *processes* that shaped the land (Bloom, 1978). Particular quantifiable elements of the land surface, for example drainage density, are direct results of the forces and processes that shape the land. By combining these quantifiable landform elements taken from stable, mature landforms in the vicinity of the project, the designer can make a design for reclamation project that can be expected with a very high degree of confidence to perform similar to the stable, mature landforms from which the design elements were measured.

Consider a pile of loose earth material in a given area subjected to a rainstorm. The water runs off the top of the pile flowing downward under the force of gravity, always seeking the lowest elevation until it leaves the given area at the lowest elevation.

The lowest elevation point is the *local base level elevation.* The erosional processes that will shape the earth material are functions of this local base level because the erosive energy at a point on the pile is a function of the elevation difference between that point and the local base level. The *slope at the local base level* is also related to the energy of the water flowing at the local base level as described in stream power equations where stream power is a product of discharge and slope (Dunne and Leopold, 1978).

Erosion works upstream (headward) from the local base level to ultimately form a land surface that balances the erosive energy with the amount of earth material that can be removed from the land surface (sediment). The erosive energy is not a fixed value, but varies with the runoff energies produced by various storms. Similarly, the amount of earth material that can be removed from the land surface varies according to the earth material properties, and also the vegetation characteristics on the land.

When we speak of "stable landforms", "landforms that resist erosion", "mature landforms", etc., we are describing a landform condition that has minimal change from the variety of storms that occur over the span of a human lifetime. We understand that over geologic time, the pile would be expected to gradually wear down to the local base level elevation. Initially in the landform development, the headward erosion progresses much more rapidly. As the youthful (as opposed to mature) channel headcuts upstream, mass wasting processes deliver slope material to the channel to be transported downstream out of the area (beyond the local base level). The mass wasting processes can be augmented by moisture retained on the slope surfaces. In the northern hemisphere, the *north and east facing slopes* tend to be steeper for this reason (Dunne and Leopold, 1978). The channel will increase its length seeking to balance the erosive energy with the amount of earth material that can be removed from the land surface

If the area is large enough that a single channel cannot balance the erosive energy and sediment, the channel will extend its total length by adding tributary channels by headcutting into sediment-generating areas that are deficient in channels. This process will continue until the channel network is sufficient to achieve this balance. The length of channel divided by the land area that they drain is the *drainage density* value. By considering these processes, it can be understood that a youthful landform of a given earth material in a given climate will have a lower drainage density value than a mature landform in the same conditions.

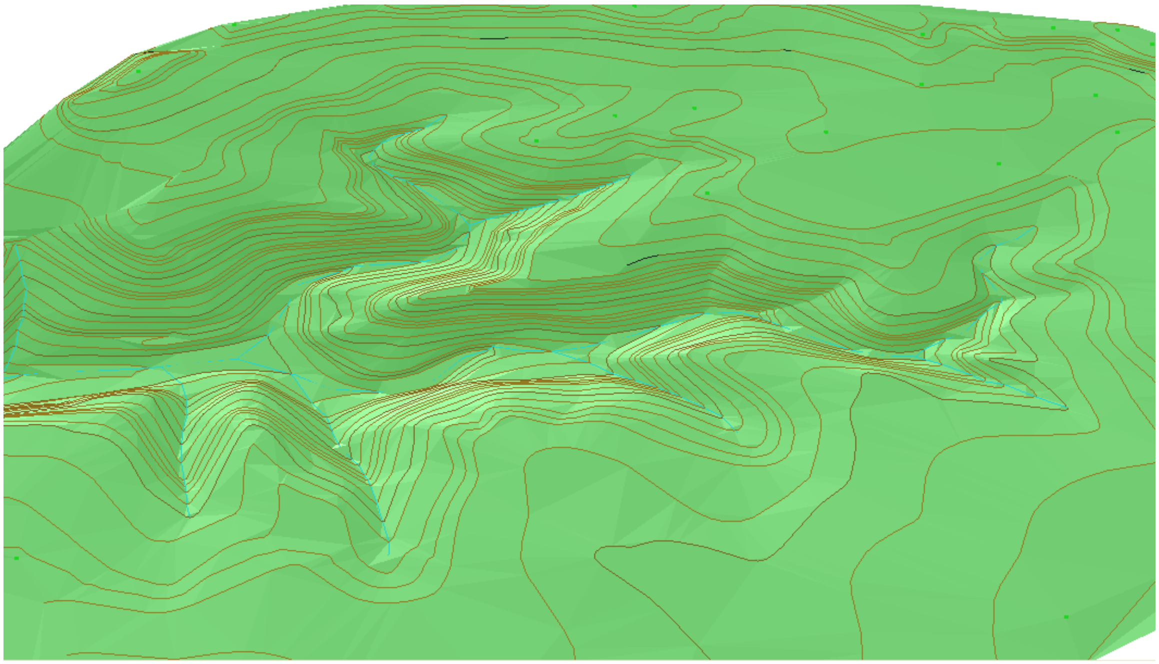

Figure 1. Three dimensional surface model of a landform that has achieved geomorphic stability when drainage density, channel geometry, complex slope profiles have been optimized. Note the smooth contour bends and the smooth transition from the convex area above the channels to the concave channel profiles.

This dissection of the pile will continue until the erosion forces are in balance with the resisting forces. Then the water discharge from the pile will be in balance with the sediment volume that needs to be regularly conveyed from the pile and the 'stable landform' is achieved. The forces resisting this dissection of the pile by stream channels include the cohesiveness and particle size of the earth materials and the vegetation cover percentage and binding by root systems. This dissection stops at the head (beginning of each channel).

The mature *channel longitudinal profile* in the loose earth material will be concave from its head to its mouth to adjust the erosive energy to maintain stability. This is because the upper reaches have the least stream discharge and erosive energy and can remain stable at steeper slope values, the mid-reaches have greater discharge and erosive energy and can remove material from the slope, and the lower reaches with the greatest discharge must decrease the slope to keep the erosive stream discharge energy in the stable range. The resulting channel longitudinal profile, steep, then less steep, and finally least steep, is concave and the landform is again the result of the process.

The pile above the channel's head can remain convex in the mature landform because the amount of water there is relatively small and when combined with the flatter slopes at the top of the pile has less erosive energy to change the form there. This distance from the ridge to the head of the channel results from the interaction of the local climate, earth materials, and vegetation and is a characteristic of landforms in an area that can be called the *ridge-to-head-of-channel distance* (Bugosh, Nicholas, 2006). Figure 2 gives a quick visual indication of how similar this value is in an area and field measurements confirm this perception.

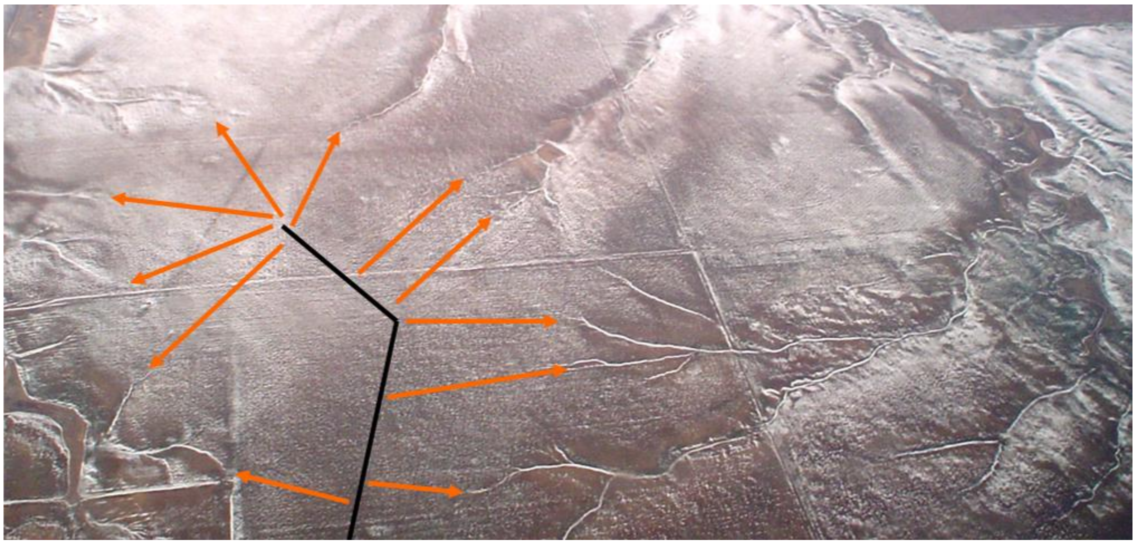

Figure 2. The consistency of the ridge-to-head-of-channel distance (black line is ridgeline, CO) can be gauged by comparing the consistency of the length of the orange arrows. Also note the degree and distribution of the drainage density dissecting the land area.

The elements that have emerged in this discussion of landform evolution thus far are:

- Local base level elevation
- Slope at the local base level elevation
- Slope steepness and aspect
- Drainage density
- Channel longitudinal profile
- Ridge to head of channel distance

Stream channel plan and cross-sectional morphological characteristics

The plan view and cross-sectional forms of the stream channels are also related to the landform above the stream's water surface. When water flows for a distance over land, it does not tend to follow a straight course, but rather begins to wander back and forth. The physical mechanism for this phenomenon is not fully understood, but this behavior is universally observed. One effect of this meandering is that the added length of the channel increases its flow length between upstream and downstream elevations and effectively reduces the slope and erosive energy of the stream. The ratio of this stream flow length to valley length is called *sinuosity.* Another effect of this meandering is to create an alternating series of ridges on the contiguous upland landform.

Plan view geometry. Hydrologists working on perennial streams have established mathematical relationships to relate components of this meandering pattern, including radius of curvature, meander length, and meander belt width to stream discharge at about mean annual recurrence *(bankfull discharge width)* interval, for lower-gradient, valley-bottom types of streams (those generally less than about four percent slope) (Williams, 1986).

Less work has been done on steeper (greater than about four percent) stream types. These are often ephemeral reaches or smaller, tributary streams. Their plan view pattern tends toward a zigzag shape rather than the smooth radius of curvature pattern of lower-gradient streams as can be seen in Figure 3. This zigzag steam pattern defines the toes of subwatersheds that break up the overall right and left bank slopes of the channel into a mosaic of much smaller slopes. When the landform has reached maturity, the area of these subwatersheds does not generate enough runoff to result in excessive erosion based on the local climate, earth material, and vegetation.

Figure 3. High gradient channels have formed on either side of the ridgeline in the center of the image (Idaho). Note the characteristic zigzag channel pattern and the absence of rills and gullies in the subwatersheds draining to these ephemeral channels.

Cross sectional characteristics. The lower-gradient types of streams typical have higher *width to depth ratios* than the higher gradient types and often flood ‘over their banks’ onto a contiguous flood-prone area during greater discharges (Rosgen, 1996). Both the lower flow channel below bankfull stage and the flood prone area are parts of the active channel.

Conversely, the higher-gradient types of streams typical have lower width to depth ratios than the lower gradient types and contain their flood flows in a flood prone area within narrow banks.

The channel's cross-sectional area needs to continually increase in the downstream direction as function of discharge (except for the unusual case where channel leakage maintains constant discharge through a reach) to maintain stable water and sediment discharge.

Relationships of channel and upland morphological characteristics

The zigzag pattern of the steeper channels results in a series of alternating ridges and opposing valleys that break the slope into smaller subwatersheds. One zig or zag distance can be called the *"A-channel" reach length* (Bugosh, 2006). Two of these lengths define the either the toe of a subwatershed valley on one bank of the stream channel or the toe of a subridge on the opposite side of the stream channel. The size of these subwatersheds in the mature 'stable' landform is minimized to the point where the erosive energy of the runoff ceases to degrade the slope. In other words, erosion is so small as to not be noticeable in the scale of a human lifetime.

The over-bank floodprone areas of the lower-gradient valley bottom channels lead to much more subdued subridge morphology. The inside of the meander bends is the toe of a 'ridge' than can get inundated during flood discharges. This ridge trends up toward the riparian area and valley walls, but may have been obscured by alluvial deposition if the channel moved across the valley floor over time. The valley-bottom channel pattern may be less directly related to the subwatershed morphology than with the steeper channel types for this reason. The high width to depth ratio channels can be expected to have over bank flood prone areas that are expressed as wide valley bottoms.

This discussion has described how water from rain or snow-melt runoff flowing off a pile of loose earth material makes a stable, mature natural landform over time and how definitive elements of the resulting form have resulted from the processes that made them. The landform is then described as mature or stable because it has arrived at a configuration that is adjusted to local conditions to minimize further erosion. At that point, the landform exerts major control on the erosional processes.

It follows that if the designer quantifies these landform elements as they are expressed in a mature landform in given area and integrates them all into a design for a disturbed area, the resulting design can be expected to control the erosional processes in the reclaimed area to the same degree as the mature natural landform from which the design elements were measured (Ramsey, et al., 2003).

Additional elements that have emerged in this discussion of landform evolution include:

- sinuosity
- bankfull discharge width
- channel width to depth ratio
- “A-channel” reach length

Integrating all the landform elements discussed above into a reclamation design involves quantifying the local fluvial geomorphic landform, performing a great number of calculations, and then outputting the results of the calculations in a form, like construction drawings or a three-dimensional surface file, that can be used to guide construction workers to build the design. Formerly this was a daunting task, but the GeoFluv™ approach makes this process manageable, especially when used in computer software like Natural Regrade. Fluvial geomorphic reclamation designs made using the GeoFluv™ approach have been shown to be more conservative than theoretical erosion limits predicted by the SEDCAD and RUSLE programs, and the constructed designs have proved the predictions by resisting erosion without need for expensive artificial sediment controls, maintenance, or repairs through extreme storms at about two-thirds the cost of traditional reclamation methods (Spotts, 2007).

Consequences when these characteristics are absent or incorrect

The undesirable consequences of not using the geomorphic landform elements in a design, or not integrating them well, can become apparent in a single runoff event, or may emerge over a period of smaller runoff events. The following examples of common consequences of attempting to make a ‘fluvial geomorphic design’ without incorporating all the functional design elements are seen at reclamation sites not using a. By considering the inter-relatedness of the landform elements to landform function as discussed above, the reader can appreciate how a failure initiated by an error in the use of one landform element can trigger additional failures in related elements.

Incorrect values for local base level elevation and downstream slope

If the local base level elevation is too high, water will impound against the natural ground downstream of the reclamation. If the local base level elevation is too low, the processes of channel incision and headcutting will be initiated to adjust the channel elevations to the correct local base level elevation. The incision and headcutting will also combine to adjust the channel longitudinal profile. As the channel changes elevation, the upstream slopes draining to both channel banks will also adjust to their lowered toe elevations by erosional processes.

A similar effect can occur if the slope upstream of the local base level elevation is lower than the downstream slope and the bed material is loose. This mismatch of slopes creates a *knickpoint* as show in Figure 4 below. In this case the sudden increase in erosive energy created by the increased slope at the knickpoint will trigger down cutting that will persist until a new concave longitudinal channel profile from the channel's head elevation to its base level elevation is established and all the upstream slope surfaces draining to both channel banks will also adjust by erosion.

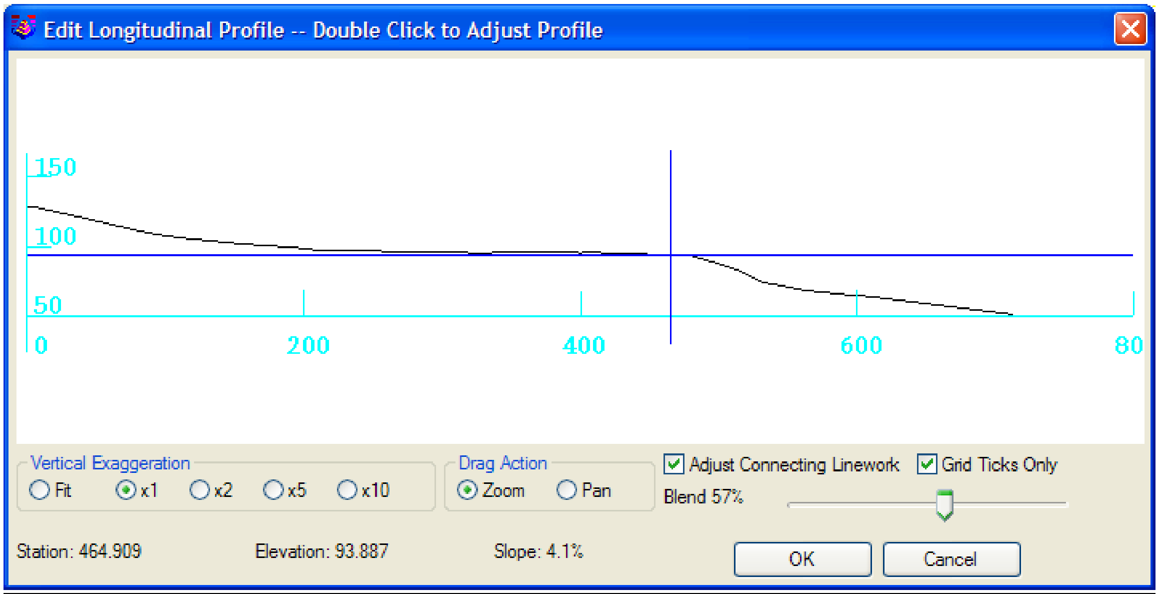

Figure 4. The blue crosshairs are set on a knickpoint in this channel profile. A stable channel profile in unconsolidated material will be convex from the head elevation to the mouth elevation (the channel's local base level).

Improper slope steepness and aspect

Normally in the northern hemisphere, the north and east facing slopes retain more moisture because the solar heat is greater later in the day when the sun's rays are concentrated on the south and west facing slopes (Dunne and Leopold, 1978). One response of this combination of solar intensity and moisture is that a plant mosaic develops with trees favored on the cooler, wetter, and steeper north and east slopes and grasses favored on the warmer, flatter, and drier south and west facing slopes. If the slope steepness and aspect do not combine to produce conditions favorable for the vegetation in the area, reclamation efforts to achieve vegetation species composition and diversity may be frustrated and unsuccessful.

Inadequate drainage density

If the reclamation design is deficient in channel length for the given reclamation area, the response will be that the channel network will add the necessary length to achieve the required drainage density through erosion. Figure 5 below shows the early phases of slope erosion to increase drainage density; eventually one or more channels will become dominant and transport the water off the slope. If the reclamation design has greater channel length than is necessary for the given reclamation area, the response will not be greater erosion because there is less land area associated with water discharge at any point.

Figure 5. The rilling on this slope is the result of inadequate drainage density coupled with incorrect longitudinal profile.

The design's drainage density can also cause problems if the channels are not evenly distributed in the reclamation design. In Figure 6, both watersheds have the same area and the same length of valleys, so the calculated drainage densities are the same. However, the watershed on the left has its dendritic pattern drawn to more uniformly dissect the watershed into smaller portions and convey the runoff and sediment from each subwatershed. The watershed on the right has all its valleys drawn on its eastern side and would tend to erode channels into the area on its western side. The d**rainage pattern** on the left is better for a stable reclamation design, because the drainage pattern on the right would tend to erode the land in the watershed's western area to develop the required drainage density there, whereas the pattern on the right tends toward stability.

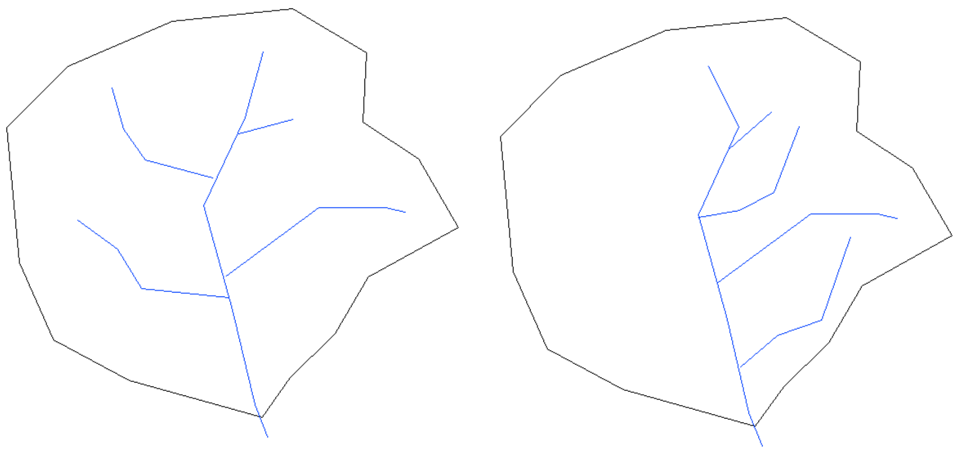

Figure 6. Comparison of evenly dissected landscape (left) and landscape with valleys concentrated in one area (right). The calculated drainage for both landscapes is identical.

Incorrect channel longitudinal profile

The longitudinal profile in Figure 4 above has a knickpoint at the station 484 feet downstream. The channel will erode through this knickpoint if the reclamation is constructed in unconsolidated material. As stated above, when the channel erodes downward the landform to either side of the channel will also erode to adjust to the eroded channel bottom elevation. If the knickpoint was made of solid rock, the channel could be stable with separate reach longitudinal profiles upstream and downstream of the knickpoint.

Incorrect ridge to head of channel distance

When runoff flows overland for the ridge to head-of-channel distance taken from a mature landform, the coalescing runoff has gained sufficient discharge energy to begin eroding a channel. When a channel is not designed into a reclamation landform using this ridge to head-of-channel distance (or less), erosion (headcutting) will occur to adjust the channel to that distance. Conversely, when the ridge to head-of-channel distance is appropriate, the channel will not headcut.

Incorrect sinuosity

The channel sinuosity affects the slope of the stream and this needs to be consistent with the required up- and down- stream channel slopes or the channel will adjust through incision and bank erosion similarly to the descriptions above in the sections on slope at the local base level elevation and longitudinal profile. It should also be noted that an arbitrarily high sinuosity value, for example when attempting to artistically add interest to the landform, may result in a channel design that is incorrect for the discharge values to which radius of curvature of the channel bends, meander length, and meander belt width are related (plan view channel geometry). The result of this mismatch can be a channel avulsion in which the channel cuts across a tight bend and initiates a series of erosional adjustments to reach a stable configuration.

Incorrect bankfull discharge width

Because water surface width at bankfull discharge has been related to plan view channel geometry (radius of curvature of the channel bends, meander length, and meander belt width) in lower gradient valley bottom stream channels (Williams, 1986), incorrect water bankfull width will result in an incorrect channel plan view geometry that the stream will adjust by erosion.

Incorrect channel width to depth ratio

The width to depth ratio affects the stream's ability to transport sediment efficiently. If the stream is over-wide, it will lose the ability to carry its sediment load and deposition will result. The sediment deposited on the channel bottom can deflect stream flow and cause bank erosion, and the caving bank can then cause deposition in the channel at that spot resulting in the continuation of the process of adjustment by erosion and deposition. If the stream is too narrow, its velocity or depth must increase to convey its discharge through the channel and the increased velocity can result in increased erosional forces that can erode the channel banks to widen the stream to a stable cross section.

If the channel's cross-sectional area does not continually increase in the downstream direction as function of discharge, then the water and sediment discharge will not perform as in stable channels.

Incorrect "A-channel" reach length

An 'A-channel in the Rosgen classification scheme refers to a channel whose slope is in the four to 10 percent range (Aa+ can describe those whose slope is greater than 10 percent) (Rosgen, 1996). An overly long 'A-channel' reach length (this term is used in the GeoFluv™ approach to refer to any channel with a slope greater than four percent) will result in larger subwatershed areas contiguous to the channel that can generate erosive runoff energy sufficient to lead to rill and gully formation on the subwatershed slopes. A shorter than necessary 'A-channel' reach length will be associated with smaller subwatershed areas and thus be a more conservative design to resist erosion, but will also add unnecessary difficulty to its construction.

The proceeding discussion has sought to clarify the relation of the reclamation land *form* to the *functions* needed to maintain its long-term stability against erosion. The need to integrate the various landform elements into a single functional landform should be apparent. That this successful integration involves considerable calculation and assemblage of the results into a suitable output format for construction may also be apparent, but intimidating. Fortunately, the personal computer is an ideal tool to take the necessary input values, make the calculations, and output the complex design in a suitable format.

Personal Computer Helps Integrate Fluvial Geomorphic Landform Design

The GeoFluv™ approach to landform design is used to make the algorithm for computer software called Natural Regrade (Bugosh, 2007). The software has a user-friendly format that is designed to lead the user through the design sequence that will result in a landform consistent with fluvial geomorphic processes. The input values are determined empirically in the project area from mature, stable landforms of similar earth material. The user can have a high degree of confidence that these input values, taken from landform elements that have formed in response to thousands of years of storms of small to extreme magnitudes, will produce a reclamation landform that behaves similar to the stable, natural landform.

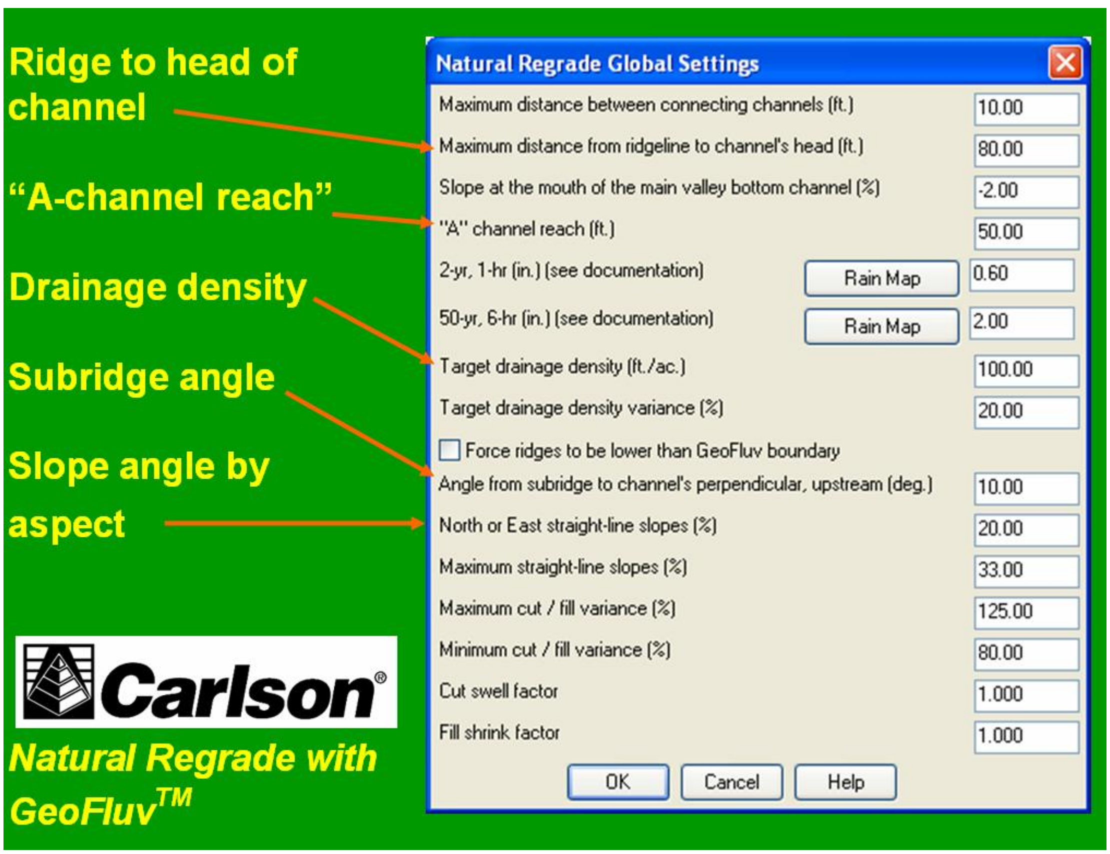

Figure 7. The user can easily use the input dialog box for GeoFluv™ values that apply to entire project area in the Natural Regrade software.

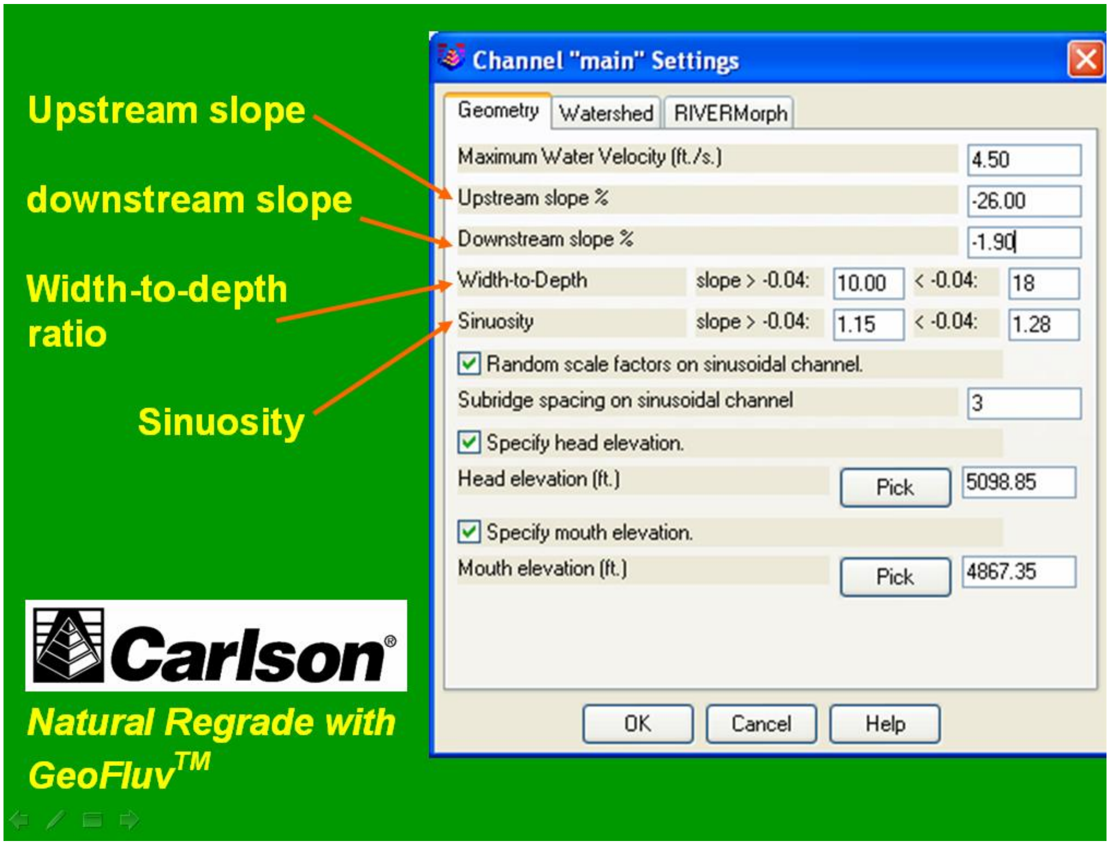

Figure 8. The user has similar ease to input GeoFluv™ values that apply to a specific channel watershed in the project area using the dialog box in the Natural Regrade software.

Verifying the Use of the GeoFluv™ design method for Stable Landform Design

That the constructed reclamation landforms do perform similar to the stable natural landforms has been demonstrated at projects at which 25-yr, 50-yr, and 200-yr storm events caused no need for repair and maintenance of upland slopes or stream channels. In several of these instances, the reclamation area did not yet have vegetation established and the GeoFluv™ –designed landform provided this resistance to erosion by itself. Figure 9 shows an example of a 68-acre site that withstood 25-yr, 6-hr and 50-yr, 4-hr storms without any vegetation cover, and a 200-yr, 3-hr storm 10 weeks before the image was made with only the vegetation from a single growing season. No maintenance or repair was needed and no artificial erosion control measures were used in construction of the site. The results indicate that the GeoFluv™ design method can produce landforms that are stable against erosion and promote sustainable land development when the appropriate local input values are used (Spotts, 2007), (Bugosh, 2006).

Figure 9. A west-facing view of a constructed GeoFluv™ design that has remained stable after exposure to 25-yr, 50-yr, and 200-yr storm events. The snow covered slopes at the left have a northern aspect and the dominantly south-facing slopes to the right have melted and sublimated their snow cover because of greater exposure to the sun. Note that the subwatershed valleys on the south-facing slope provide additional diversity in moisture harvesting because of their differing exposures to sunlight. In addition to stability against erosion, these slopes provide habitat for diversity in vegetation and wildlife and livestock use.

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