AN ABSTRACT OF THE THESIS OF

Bran Black for the Degree of Honors Baccalaureate of Science in Geology
presented on August 24th, 2009. Title: Core Site Sediment Sources off of Sumatra.

Abstract Approved: _____

Chris Goldfinger

The intention of this honors thesis was to define the boundaries of the basins responsible for feeding

sedimentary materials to the core sites taken for the 2007 OSU Sumatra Cruise. These boundaries were

defined with the specific use in mind of tracking potential sources of material that would likely be

incorporated into earthquake induced turbidites found at the sites that were cored. The approximate

basin and subbasin boundaries were ascertained via two separate methods. The resultant stream

system was then used to produce a geometric network capable of tracking connectivity, upstream

accumulation, direct pathways, and a variety of other functions between a specified core site and any

other chosen location that retains viable connectivity with the core site in question. These analysis

capabilities, as well as the mapped basin and subbasin boundaries, will hopefully be useful in the further

understanding of the transport of sedimentary materials at this study site.

Key Words: Basins, Turbidites, Sumatra

Email: segoblue@yahoo.com

Core Site Sediment Sources off of Sumatra

by

Bran Black

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Geology (Honors Scholar)

Presented August, 24th 2009
Commencement June 2009

<u>Honors Baccalaureate of Science in Geology</u> project of <u>Bran Black</u> presented on <u>August 24th, 2009.</u>

APPROVED:

_____

Mentor, representing Geology

_____

Committee Member, representing Geology

_____

Committee Member, representing Geology

_____

Chair, COAS

_____

Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

_____

Bran Black, Author

Acknowledgements

Chris Goldfinger, Chris Romsos, Dawn Wright, Peter Ruggiero, and Ann Morey-Ross have all been exceedingly helpful in my completing this project and I would like to thank them all for the time and advice they've given me.

Table of Contents

List of Figures

Dedication

Thanks Mom, Dad, Chels, and Tiff. You know what all for. Dad: Quantum materiae materietur marmota monax si marmota monax materiam possit materiari? Yadaouisi? Just kidding. Nietnienno. But probably about 6 cords. Cords, not chords. Or the other kind of cords. Or the other other kind of cords. Or the other kind of chords, you know, different than the first kind of chords. Mom: Don't worry about the penny if you read this. It was in his pants pockets when he left. That's why you should always clean your pockets out when you do laundry – what would have happened if he'd pulled out some lint? Chels: So far as I can tell, there really is water at the bottom of the ocean, but I could be wrong on this of course. Tiff: Draco Dormiens Nunquam Titillandus, but I never would expect you to anyway. I hope. Please please please please *please* tell me you wouldn't…

Thank you too, Tailler. I miss you.

Background

The study of marine sediment cores can aid in deriving the recurrence interval of earthquakes within a study area. The record found in these cores reflects the disturbances created by earthquakes (and possibly other sources) via the presence of turbidites. Turbidites appear in cores as patterns of repeating layers of coarser materials that trend toward finer sediments while moving upward through the core. In the context of the Cascadia subduction zone, the signature that earthquake induced turbidites have left behind illustrates how the region off of the Washington, Oregon, and Northern California coasts is capable of producing $\sim M_w$ 9 earthquakes (Goldfinger et al., 2008). Estimates such as these have led to elevated concerns about the hazards faced along Pacific northwestern coasts, such as the potential that:

> "Damage, injuries, and loss of life from the next great earthquake … [is expected to] be great and widespread, and will impact the national economies of Canada and the United States for years or decades." (Penrose, 2000).

Off of the island of Sumatra, in the same region that encompasses the epicenter of the December 26th 2004 Earthquake, there is a similar geologic regime in operation. The accompanying tsunami, also called the Boxing Day Tsunami, led to the deaths of over a quarter of a million people. This fact, as well as the fact that similar earthquake events occur off of our own shores here in the Pacific Northwest, gives us a great impetus to study the conditions that produce megathrust earthquakes.

The caveat in using sediment cores for this type of research stems from the fact that turbidites may be initiated by a variety of triggers, which have the potential to produce turbidites with similar, or possibly identical, identifying characteristics (Edwards 1993, Nakajima 2000). In order to negotiate this obstacle, certain techniques have been established to winnow the non-earthquake induced turbidites from the

true earthquake produced turbidites that are being targeted within the sedimentalogical record for this research (Goldfinger et al. 2008; 2009).

The purpose of this project is to determine the boundaries of all basins that were cored for the 2007 OSU Sumatra cruise. Additionally, it was designed to help determine the connectivity between separate core sites throughout the study area, and whether or not these sites may potentially share the same sources of sediment materials during a turbidite event.

Fig. 1: Plate Motion Near Sumatra

http://walrus.wr.usgs.gov/tsunami/sumatraEQ/images/ionetec _major_faultsm.jpg

If it can be shown that corresponding sequences of earthquakes are found in cores that do not share the same sources of sediment, this is a strong indication that the turbidite record is indeed displaying the results of past earthquakes, and not a random sequence of turbidites that were not related to each other across the entire range of the study site.
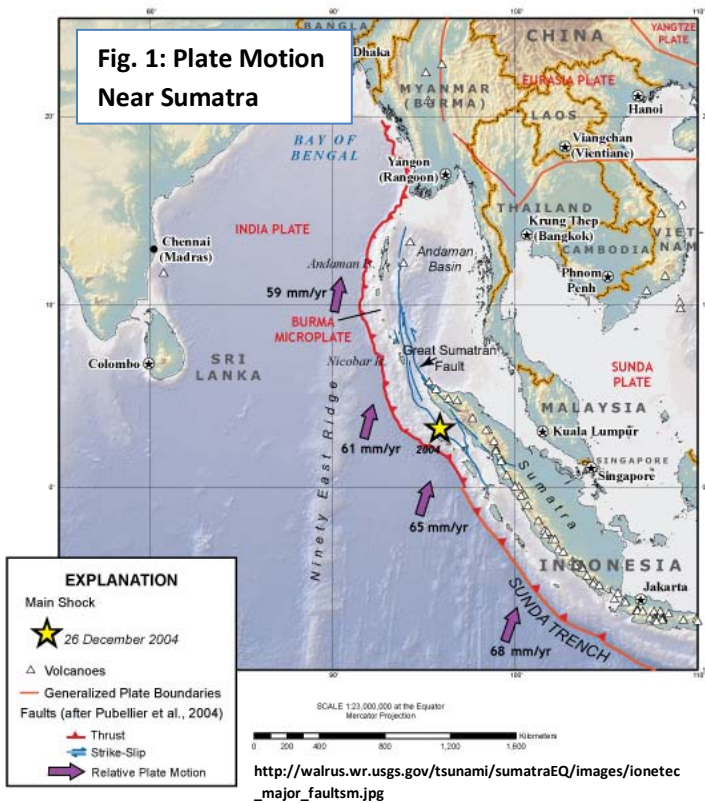
Geology of Sumatra

Roughly 90 million years ago, the Indian continent began to separate from the larger Gondwanaland continent. Large amounts of vertical elevation gain and thrusting later began around 36-37 million years ago at the end of the Eocene. At roughly 21 million years ago, the rate at which the Indian subcontinent was travelling northward declined sharply, probably indicating the impact between the Eurasian and

Indian plates. At some point around 17-19 million years ago, spreading began along the Mid Ocean Indian Ridge. Subduction of the Eurasian plate stopped, while the impact of the two plates began to produce the Himalayan mountain range we see today via the action of crustal shortening. This same mechanism began to close the Tethys Ocean, which had been the water body north of the Indian plate prior to its collision with the Eurasian plate.

The Indian Ocean is home to a plethora of fracture zones, ridges, and basins. Until recently, the northern Sumatra-Andaman Subduction Zone was thought by some to be aseismic, having little or no earthquake activity due o the high obliquity of subduciton. The area that makes up Sumatra itself includes an "active belt" and a mountain range that sweeps through from Myanmar in the north to the Andaman-Nicobar Islands and ends off to the west past Java (Rao and Griffiths, 1998).
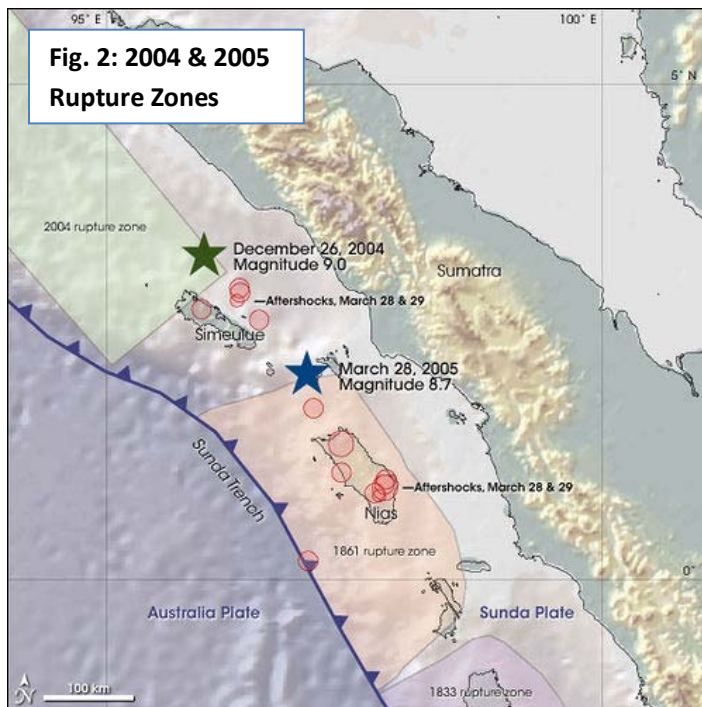
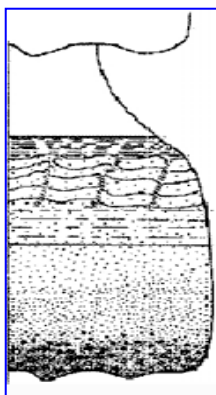

Fig. 2: 2004 & 2005 Rupture Zones

The Boxing Day Earthquake produced a ruptured zone of roughly 1200-1400km along the plate boundary, extending to the south the island of Simeulue and along the Sunda Trench. The 2005 earthquake initiated a 300 – 400 km rupture off of Nias Island (Ladage et al 2006).

Turbidites

In many respects, turbidites behave very similarly to landslides. They are a common mechanism that transports sediments off of the continental shelf, relocating a large amount of material compared to the amount moved tides, ocean currents, or waves. They can be triggered by a variety of means, for example, via density undercurrents comprised of suspension layers on shelves, from ashfall, tidal or storm produced surges, storm or tsunami wave loading, or river discharge (Edwards, 1993). Additionally, they may be initiated by volcanic eruptions, slope self-failures, sea level fall, tides, and tsunamis (Nakajima, 2000).

A sediment flow is a "mixture of particles and water that move down slopes because mixtures have a greater density than that of the ambient fluid." Turbidity or density currents remain intact so long as there is enough upward momentum remaining in the flow to keep sediments in suspension. Hence, a sediment flow holds much in common with a turbidity flow, which in turn produces turbidites (Edwards, 1993). The flow will remain in motion if the shear stress produced by downslope gravity as related to the shear stress on the suspended grains remains greater than the "frictional resistance to flow", and while the grains cannot easily settle because of the continued presence of a support mechanism (intergranular flow, grain interaction, turbulence, or matrix strength). As evidenced by the Grand Banks Turbidite of 1929 that traveled at least 648 km, these mechanisms may drive a flow for great distances.

grain size	Bouma divisions	interpretation
mud	pelite	pelagic sedimentation or fine grained, low density turbidity current deposition
silt	upper parallel laminae	?
sand	ripples, wavy or convoluted laminae	lower part of lower flow regime
	plane parallel laminae	upper flow regime plane bed
sand ---> to granule at base	massive, graded	upper flow regime, rapid deposition and quick bed

The Bouma Sequence is the most widely used model that describes the facies within a turbidite. Termed as both "intervals" and "divisions", five different groupings are often used to describe the various facies that may be found in a complete turbidite record. These units include: A) graded, B) lower parallel laminae, C) current ripple laminae, D) upper parallel laminae, and E) pelitic intervals or divisions. In reality, it is not common to see all five intervals in contiguous order before the sequence begins again; however, these are the five potential divisions that may be found in a turbidite record (Edwards, 1993). The essential trend that these intervals display is consistent upward fining (or put another way, finding consistently finer grains higher up in the sequence than toward the bottom) a signal that can be used to help identify the presence of a turbidite within a sediment core.

Types of Turbidites

Turbidites have two end-members, coarse grained (sand rich), and fine grained (mud rich), with coarse grained turbidites being more predominant in active-margin systems. Coarse grained turbidites tend to prograde into basins at a slow rate, simultaneously decreasing in the thickness of their deposits. Fine grained turbidites occur at both active and passive margins, prograde at a more rapid rate than coarse grained cases, and form deposits in the distal fan. Tectonically active basins tend to have coarser turbidites filling them than passive ones (Bouma, 2004). Fine grained/mud rich turbidites are more common at passive margins that have efficient basin transport, a broad shelf, are often delta-fed, and

usually have long fluvial transport. Usually they display a higher sand to shale ratio at the base of the slope, shifting to a low ratio in the mid-fan region, and back to a high ratio at the outer fan. Coarse grained/sand rich turbidites often have inefficient basin transport systems, a narrow shelf, and have canyons as a source, which work together to produce a prograding fan. The higher ratio of sand to shale lowers as distance from the channel increases and the turbidite gets closer to the outer edge of the fan (Bouma, 2000).

Affect of Terrain on Flow of Turbidites

The terms ponding and containment are used to describe the situation when a turbidite is contained either completely or almost completely within a basin (Lomas 2004). The shape of the basins themselves is predominately dictated by four factors; sea-level fluctuation, sedimentary characteristics and processes, tectonics, and climate (Bouma 2004). Submarine basins appear to have a great impact on the manner in which turbidite deposits or laid down, or, as Lomas puts it,

> "… a wealth of case studies now available from many contrasting turbidite systems worldwide makes it clear that, in many basins, both sediment dispersal patterns and the geometries of depositional bodies have been profoundly affected by pre-existing or developing basin-floor relief." (Bouma 2004).

Furthermore, it is possible that portions of a turbidite could be "reflected" when they encounter an obstruction, such as outcrops or bounding slopes (Lomas 2004).

Debris Flows vs. Turbidites

Certain characteristics differ between debris flows and turbidites, as debris flows tend to maintain the same density throughout their deposit. This is not the case for turbidity currents, which may have shifting densities due to differing deposition, entrainment, and erosion rates throughout their emplacement. Debris flow will often (when started on the slope above a basin) build a deposit that starts near the beginning of the flow at one thickness and will thicken slowly as it spreads outward, coming to a sudden stop just before the head of the basin. Contrastingly, turbidity currents will deposit on basin floors almost exclusively and will exhibit a region of erosion between the scarp and the area material was deposited in. Additionally, the turbidite will be most substantial at the base of the slope and will thin as it spreads toward the basin (Pratson et al, 2000). Tsunamis produced by landslides can have long run-ups onto land, but usually they do not encroach onto land for a great distance, and are also generally found over a smaller range coastline than tsunamis produced by the subsidence of the seafloor during an earthquake. Subsidence is also paired with coseismic uplift on land that is usually on transoceanic or regional scales (Carver, 1996).

Using Turbidites as Paleoindicators of Earthquakes

Most turbidites start on the in submarine canyons, which act as a gateway servicing both shallow and deep water regimes. Nonetheless, it is possible for the triggers that initiate turbidites to operate at greater depths (Nakajima, 2000). Due to these factors, Nakajima states that the recurrence intervals of earthquakes cannot be approximated via the examination of turbidites in coastal basin along narrow

shelves. However, Nakajima suggests that it may be possible to apply this type of test where "structural highs", such as ridges, separate the basin from the shelves (2000).

In the case of Sumatra, there are a series of topographic features that help to reduce the chance of non-earthquake induced turbidites creating a large impact on the sedimentological record of the region. The island of Sumatra, as part of this subduction zone's forearc basin, creates a large and effective barrier against storm induced turbidites making their way into the study area situated south of Sumatra. Sumatra's northerly presence also precludes outlets for the northern basins, as the result of the sedimentary material transported off of Sumatra filling the trench at a slower rate than uplift is occurring.

The Bengal and Nicobar Fans were sources of sedimentary material up to the Pleistocene; however, from the beginning of the Holocene to current day (encompassing the period sediments sampled by OSU's cores date from), it appears that transport may have been cut off from these sources, possibly due to either obstruction from the NinetyEast Ridge, or the occurrence of a large Pleistocene era slide that appears to have choked off transport to the north. Hyperpycnal flows are also unlikely to produce large amounts of turbidite activity, as there is a dearth of rivers in these islands capable of producing such flows in the areas that were cored.

Mass self-failure is a possibility, but as with the previously listed potential triggers, is spread only over a discrete spatial domain and would not be responsible for turbidites produced over a large areal extent. The presence of hydrates or tectonic uplift may decrease the cohesiveness of the sedimentary units on site, but are not triggers in and of themselves, only producing conditions that may increase the ease of slide activity.

Although it is still quite possible that certain specific turbidite events found in the study area could be attributed to other causes beside earthquakes, large scale, similar, synchronous turbidite records are

best and most simply explained by earthquake inducement, rather than smaller scale discrete events

(Dr. Chris Goldfinger, personal communication, August 22nd, 2009).

Finding Flow in Study Site

For the sake of clarity and brevity, details on the procedure used to produce the datasets in this analysis have been placed in Appendix A at the end of this report.

Fig. 4: Core Site Basins
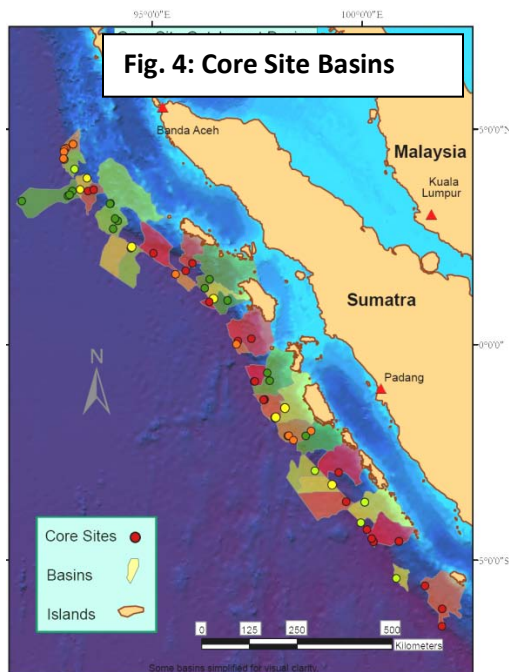
The basin boundaries were decided on by examining various bathymetry datasets gathered on site. These datasets were then used to find the breaking points in the terrain where a turbidite would likely be able to traverse through, and where it would be halted by terrain.

Terrestrially, a watershed is a tract of land over which any raindrop that falls within its boundaries will eventually make its way to a common outlet. Its edges are defined by ridgelines that separate adjacent watersheds. If one of these ridgelines were running north to south, and a raindrop fell slightly to the west of the ridge, it would flow into the watershed to the west. A raindrop that fell to the just to the east would find its way into the eastern watershed. At the ridge, this behavior produces flow directions that travel in opposite or nearly opposite directions.
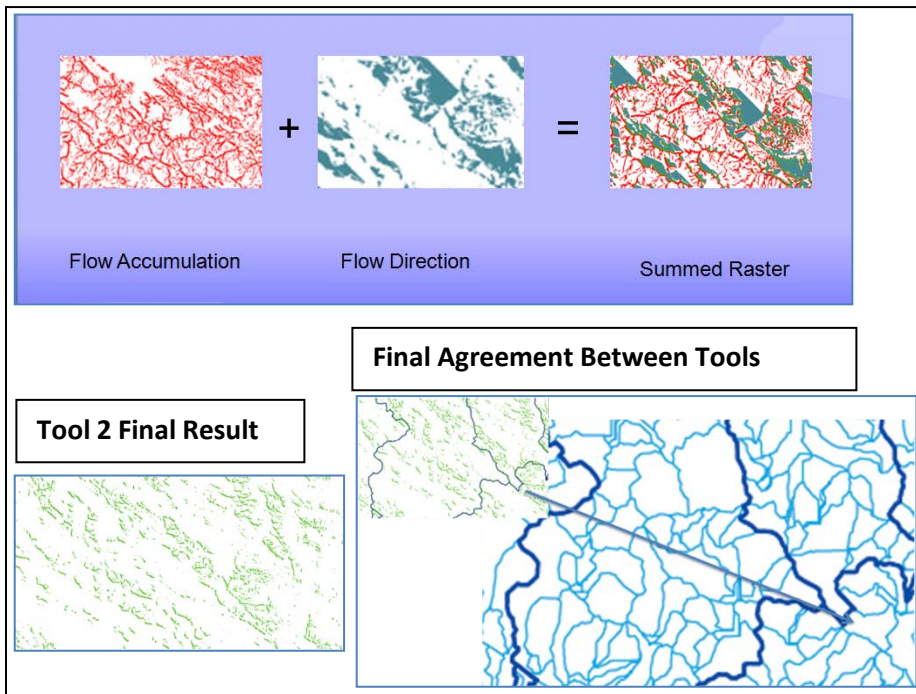
It would be unexpected to find a stream near the edge of a watershed on land, because there would not be the necessary distance traversed from the ridgeline to accumulate enough water to feed an

organized stream. Additionally, one of the defining characteristics of a watershed is that a stream from one watershed never crosses into a neighboring one, since the water would have to find a way to flow uphill and over the ridgeline in order to do so. In a marine setting, basins are the corollary to watersheds. This being the case, the word "watershed" will be referred to as "basin" throughout the rest of this report.

The results of two separate methods were compared and then used to confirm the basin boundaries for this project. Owing to the similarity of basins to watersheds, one method of determining these boundaries was via an ESRI tool called the Watershed Delineation Tool designed to define watersheds on land. In addition to the boundaries of the basins, this tool also produced a stream network based off of the main channel for each of the watersheds the tool rendered. The second tool was designed to approximate the boundaries of a basin through the selection and combination of characteristics from two other datasets, flow accumulation and flow direction. The resultant dataset was used to not only to verify the boundaries produced by the Watershed Delineation Tool, but also to ensure that the scale used by the ESRI tool was correctly selected.

One of parameters the watershed tool takes into account is the minimum number of cells that must be inputted into a region before it can be considered a watershed, which translates into setting the minimum size of watersheds that will be produced in the dataset. This problem was addressed by comparing the results of both the Watershed Delineation Tool and the second tool that was designed for this project. The Watershed Delineation Tool was run iteratively while inputting progressively larger minimum watershed size parameters until it appeared that the size of the smaller basins were best reflecting the breaks in flow that were illustrated via the second tool.

Fig. 4: Finding Basin

Flow Accumulation + Flow Direction = Summed Raster

Final Agreement Between Tools

Tool 2 Final Result

The second tool was also used to check that the ESRI tool was producing reasonable results with respect to the terrain (see Fig. 4). Where the second tool disagreed with the basins drawn by the Watershed Delimination Tool the boundaries were examined more closely to decide if they were reasonable. Once these two means of obtaining boundaries had been executed and compared, a network based on the streams running through these basins was developed in order build a dataset that could be turned into a network capable of tracking the transport of materials throughout the basin.

Streams may be modeled using a GIS by identifying cells that have a high amount of flow upstream coming into them. Two different sets of stream networks were built for this project. The first was built by the Watershed Delineation Tool, which projected one branch of stream for each individual basin. Since a watershed has only one outlet, and the streams constructed by the GIS tool represent the sites that

Fig. 6: Stream Network
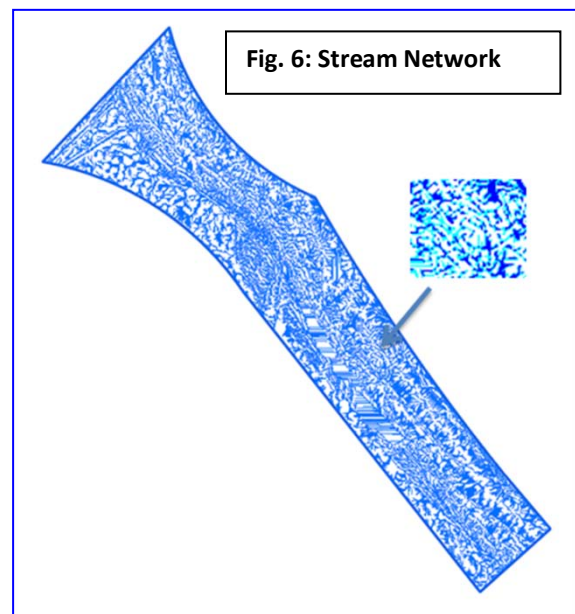
material can flow out of a watershed, or in this case, a basin. The second stream system was not used to

describe the flow of streams throughout the basin, but instead was used to highlight regions where flows were high versus where flows were low. Its purpose was to aid in the detection of ridgelines and other features that could indicate a basin boundary. By selecting for cells that have, for example, 50 or more cells feeding into them from upstream, it is easy to visualize a sort of exaggerated stream network could be used to estimate where there is a potential for flow, and where there is not. A cell having 50 cells upstream of it is not actually a high value in the context of this site, but when looking for ridgelines, it is helpful to see locations that have flow accumulating in them. Since the boundary cannot exist where there are more than a handful of cells (to take into account a reasonable window of error in the elevation data), if there is evidence of flow in a certain region, the basin boundary does not belong there. These streams were used in tandem with the results of the previous two tools in order to ensure that reasonable results were being produced.

Topology of both basins and subbasins were considered for this project. The basins describe the ultimate extent over which materials could be the source for a core situated within them, but the smaller scaled subbasins help to look more closely within the basin and determine how flow is travelling on a finer level. The streams that service the subbasins were used to construct the data that ultimately became the stream network; however, the segments of the streams that were could be considered main tributaries on the basin-wide scale can still be used "stand alone" if the data on the subbasin scale is not desired. For further discussion on how the subbasins were constructed, please see Appendix A.

This project required complete regional coverage of bathymetric data. While at sea, OSU gathered data at core sites via multibeam sonar. On a broader spatial scale, 90m British Institute data was also used; however, this dataset contained "holes" in it or places where there was no data coverage, meaning that lower resolution 1km data had to be used to "plug" those gaps through the mosaic function in ArcGIS. This approach proved to be problematic in that the edges between the low and high resolution data did
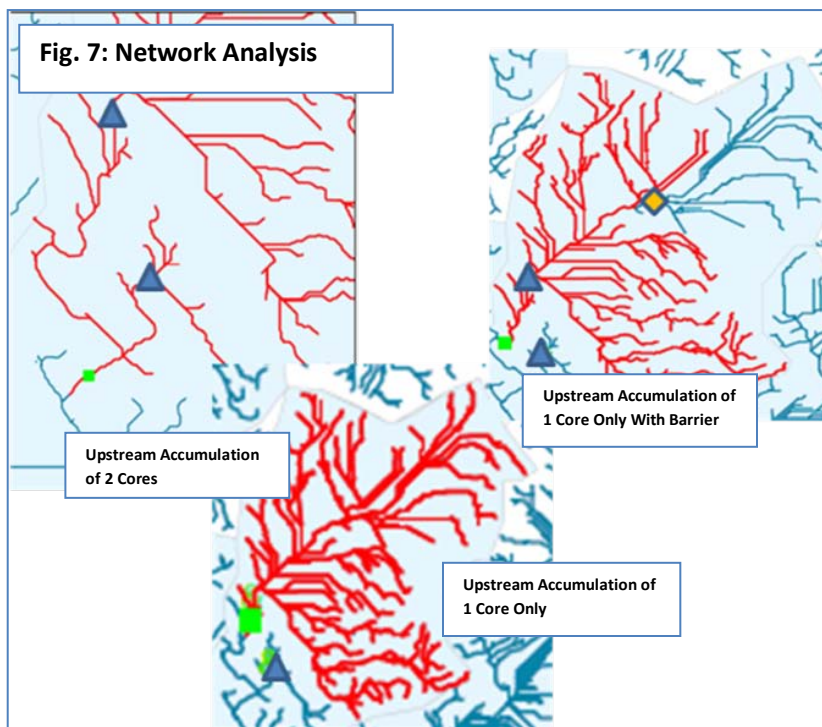
not mesh well enough to run the needed analysis on the data – producing phantom harsh edges and changes in gradients. This caused ArcGIS to interpret these artifacts as steep valleys or ridges in places that there most likely was no marked change in topography. Another type of artifact in the data is "ship tracks", or places in the data that are slightly disrupted due to additional bathemetric data gathered while the ship crossed over a previously surveyed region. A filter was used in an attempt to smooth some of these minor discrepancies in the data without changing its trends. A low-pass and high-pass filter, as well as a focal mean filter, were used on the original bathymetric data and compared to each other. The focal mean function and low-pass filter produced highly similar results, while the high-pass filter seemed only to exacerbate the imperfections in the data. The focal mean data was chosen to run the analysis, although the basins estimated by the watershed tool from the focal mean and high-pass filters were so similar that it is highly unlikely that it would have mattered in regard to the analysis which of these two filters were used. In order to check the effect of the filters, the watershed tool was run on the original data without a filter. While the majority (roughly 80%) of the boundaries were the same or quite similar, the remaining 20% percent or so displayed enough of a shift that the boundary drawn from either the filtered or unfiltered data would have been located a kilometer or more apart.

NETWORK ANALYSIS

Once the stream network from the Watershed Delineation Tool was constructed, the data was then available to build a network from this information. A network has the ability to track travel along pathways, such as streams, and can be instructed to recognize sources of flows as well as sinks. These sources and sinks can then be used to describe the routes and directions water, and ultimately a turbidite, would be inclined to traverse in a system. It then becomes possible to examine the basin as a whole, or to focus instead on certain portions of the network up or downstream from the location that

is selected. Furthermore, it is possible to trace all connected points of a system above or below two selected points, as well as between two specified locations. Additional analysis may include isolating common reaches of the stream upstream of two or more cores, or to specify areas not to be included in a query.

These capabilities, as well as many others, are useful in the context of studying turbidites because the network serves as a device that can track the areas upstream of a core that form the cummulative sources of the turbidite, and also can be used to indicate which cores are connected to the same sources upstream. Comparing the histories of these related cores can indicate whether or not flows are traveling as expected through the system, and can help ground truth whether or not the events that appear to display the same history of turbidites do or do not share the same sources of materials.

Fig. 7: Network Analysis

Upstream Accumulation of 1 Core Only With Barrier

Upstream Accumulation of 2 Cores

Upstream Accumulation of 1 Core Only

Being able to track interactions between cores indicates whether or not similar signatures found in a core should be expected because of common source histories. If multiple cores in different basins illustrate similar sequences of turbidites, the fact that they had disparate sources greatly reduces the possibility that a string of smaller scale triggers happened to initiate a series of events across the entire extent of the study area that all left behind a similar pattern. It becomes much simpler to explain the patterns shared in the histories of these cores as being

produced by broad scaled events, such as earthquakes, rather than being the results of random storms or slope failures that happened to leave behind similar repeating patterns throughout a study area.

CONCLUSION

Although care must be exercised when deciding which turbidites represent an earthquake versus a non earthquake induced turbidite, with proper precautions it is possible to use turbidites in sediment cores as paleoindicators of earthquakes. This project is meant to aid in the beginning of this overall process by helping to define the boundaries of basins that serve as sources of sediments for turbidites. A network based off of stream information derived from the basins in the study site was constructed to more easily investigate the flow of material within the basins themselves. If it can be shown that the same sequence of turbidites are occurring across multiple basins that do not share the same sources of materials, then it becomes evident that this pattern is not repeating simply due to chance. Such consistency is a good indicator of earthquakes serving as the cause of the turbidites examined in the sediment cores taken within the study area.

Bibliography

Atwater, Brian F., Eileen Hemphill-Haley. <u>Recurrence Intervals for Great Earthquakes if</u>

    <u>the Past 3,500 years at Northeastern Willapa Bay, Washington</u>. Menlo Park, Ca: United States
    Government Printing Office, 1993

Bouma, Arnold H. "Fine-Grained, Mud-Rich Turbiditie Systems: Model and Comparison

    with Coarse-Grained, Sand-Rich Systems."<u>Fine-Grained Turbidite Systems (SEPM Special</u>
    <u>Publication No. 68)</u>. 2000.

Bouma, Arnold H. "Key Controls of the Characteristics of Turbidite Systems."<u>Confined</u>

    <u>Turbidite Systems (Geologic Society Special Publication 222)</u>. 2004.

Carver, Gary A., James P. McCalpin. "Paleoseismology of Compressional Tectonic

    Environments."<u>Paleoseismology</u>. 1996.

Edwards, Deborah Anne. <u>Turbidity Currents: Dynamics, Deposits and Reversal. 44</u>

    <u>(Lecture Notes in Earth Sciences Series)</u>. Germany: Springer-Verlad, 1993.

Goldfinger, Chris; . "Cascadia great earthquake chronology based on the turbidite

    event record."

    <u>Abstracts with Programs - Geological Society of America</u> 34.5 (01 Apr. 2002): 36-36. <u>GeoRef</u>.
    EBSCO. [Library name], [City], [State abbreviation]. 9 Mar. 2009
    <http://proxy.library.oregonstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct
    =true&db=geh&AN=2003-020224&loginpage=Login.asp&site=ehost-live>.

Goldfinger, Chris; . "Holocene earthquake records from the Cascadia subduction zone

    and northern San Andreas Fault based on precise dating of offshore turbidites." <u>Annual Review</u>
    <u>of Earth and Planetary Sciences</u> 31 (01 Jan. 2003): 555-577. <u>GeoRef</u>. EBSCO. [Library name],
    [City], [State abbreviation]. 11 Mar. 2009.
    <http://proxy.library.oregonstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct
    =true&db=geh&AN=2004-014390&loginpage=Login.asp&site=ehost-live>.

    Goldfinger, Chris; . "Late Holocene rupture of the northern San Andreas Fault and

    possible stress linkage to the Cascadia subduction zone." <u>Bulletin of the Seismological Society of</u>
    <u>America</u> 98.2 (01 Apr. 2008): 861-889. <u>GeoRef</u>. EBSCO. [Library name], [City], [State
    abbreviation]. 11 Mar. 2009
    <http://proxy.library.oregonstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct
    =true&db=geh&AN=2008-084527&loginpage=Login.asp&site=ehost-live>.

Ledage et al., "Bathymetric Survey Images Structure off of Sumatra." *EOS* 87(2006): 165-

    172. Print.

Lomas, S.A.. "Confined Turbidite Systems."Confined Turbidite Systems (Geologic

   Society Special Publication 222). 2004.

Nakajima, Takeshi; . "Initiation processes of turbidity currents; implications for

   assessments of recurrence intervals of offshore earthquakes using turbidites." Chishitsu
   Chosajo Geppo = Bulletin of the Geological Survey of Japan 51.2-3 (01 Mar. 2000): 79-87.
   GeoRef. EBSCO. [Library name], [City], [State abbreviation]. 9 Mar. 2009
   <http://proxy.library.oregonstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct
   =true&db=geh&AN=2001 007565&loginpage=Login.asp&site=ehost-live>.

Penrose Conference 2000, Penrose Conference 2000: Cascadia Earthquake

   Tricentennial. Oregon Department of Geology and Mineral Industries Special Papers, 2000.

Pratson, Lincoln F, et al.. "Debris Flow vs. Turbidity Currents: a Modeling Comparison of

   Their Dynamics and Deposits."Fine-Grained Turbidite Systems (SEPM Special Publication No. 68).
   2000.

Appendix A

Data Files Inputted:

    -GPS Points of core locations

    -Bathymetry data of site

        -Spatial Reference: WGS_1984_Transverse_Mercator

        -False Easting: 500,000

        -Central Meridian: 97.5

Program Used:

    -ARCGIS 9.3

Unless stated otherwise, tool settings were left at default.

OPERATIONS

Merge in lower resolution (1km SRTM) data to "plug holes" in higher (90m) data.

    -Merge (mosaic) operation in Map Algebra

        Input 1: 90m data, Input 2: 1km data,

        Output: mos200_F

Run Focal Mean to average out edges left by Merge operation.

    -Focal Mean operation in Map Algebra

        Command line: Outgrid = FocalMean (Ingrid, rectangle, 3,3)

Input: gbj_utm

Output: mos200_F

A high pass and low pass filter were also run on the mosaiced data; however, the high pass filter only seemed to exacerbate the edges, and the low pass filter produced results so similar to the focal mean operation that there was almost no difference between the resulting datasets.

At this point, a mask was created to refine the area that was being studied and to reduce unnecessary file size.

-A polygon of the appropriate shape was created in a new shapefile. This polygon was then used to act as a mask (specified area) to select the bathymetry data from.

Input: mos200_F

Output: focmeanmask

Flow Direction

-Hydrology menu operation

Input: focmeanmask

Output: flowd

Flow Accumulation

Hydrology menu operation

Input: flowd

Output: flowa

Finding Streams

In order to determine streams, it is necessary to pinpoint which cells have a large number of cells upstream of them feeding into the original cell. The larger the number you put in as an input, the larger the amount of accumulation is needed before that cell is considered to be part of a stream. In the case of this operation, only cells that have a value equal to or greater than 100,000 cells feeding into them upstream are selected for the basin scale, or in other words, given a value of one. The subbasin scale was set at a 1,000 scale minimum. All others are disregarded, being assigned a value of zero. The larger scale was decided upon by experimenting with the scale set in the Watershed Delimination Tool and comparing the results with a second, independent tool that displayed the location of low flow accumulation and large changes in flow direction to be found at a ridgeline. The basin scale represented the overall extent that materials could have come from to feed a core that may fall within a basin. The subbasins were areas that fit within the basins that may have partly contained a turbidite, but through which there was still a path that material could potentially move through. The purpose of including the subbasins was to acquire a higher level of resolution for the stream network on a basinwide scale, especially for the case of examining a basin that contained more than one core within it. A more thorough description of both these tools is in the following two sections of this index.

Fig. 7: Basins and Subbasins (Both Tools)

Large Basins

Small Basins

Nesting of Subbasins into Basins
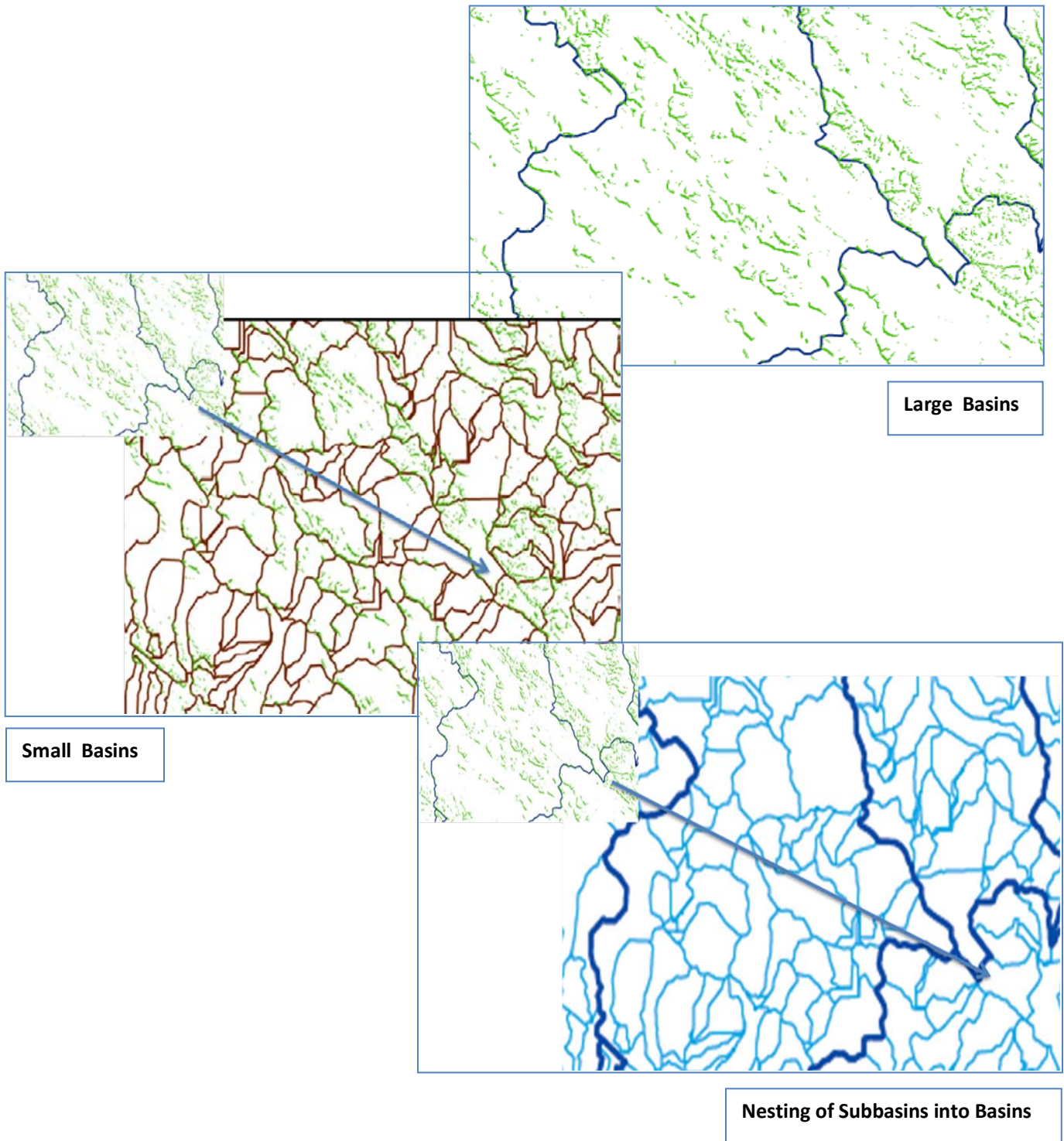
-In Map Algebra:

con(InRas >= 100,000, 1, 0)

Input (InRas): flowa

Output: st100

Command line: con(InRas >= 1000, 1, 0)

Input (InRas): flowa

Output: st1

Note: numbers in file names are factors of 1/1,000 of number of cells inputted into operation (example: 100 means 100,000 was the input).

Watershed Delineation Tool

Two tools were used to find the boundaries of the basins for this project. The results of both were compared after they had been run to serve as a check that results were reasonable.

The first tool was downloaded from ESRI.com. It automatically generates a flow direction, flow accumulation, stream network, and watershed boundary dataset from an elevation dataset.

Input: gbj_utm

Scale: 100,000

Outputs:

fa100, fd100, st100, ws100

Input: gbj_utm

Scale: 1000

Outputs:fa1, fd1, st1, ws1

Tool 2

Tool 2 was comprised of data extracted from areas of low focal accumulation and a large difference in flow direction over short distances, which are the conditions that would be expected at a watershed's boundary. A greatly exaggerated stream network was also built, designed to show locations where even small amounts of flow could potentially occur. Originally, it had been planned to make a set of ring buffers around the streams at various distances and compare how far from the streams areas of low focal flow and large discrepancies in flow direction were to take a more gradational approach, but the buffers produced such large file sizes that the operation proved to be too cumbersome to be practical. Also, areas of low slope were initially intended to be extracted and compared to the focal flow and accumulation. Unfortunately, when areas of low slopes were included as originally planned, they began to introduce other areas besides basin boundaries, introducing error if the other conditions for flow accumulation and focal flow happened to be met there (for example, in the lower slope areas outside the trench or some slopes out toward the abyssal plane).

The focal flow function was used here instead of flow accumulation because flow accumulation was dependent on what happened upstream of the cell in question, while focal flow is a type of neighborhood analysis and only takes into account what is happening on a cell by cell basis. Focal flow was selected over flow accumulation in order to better highlight what was occurring with the terrain on a smaller scale basis, hopefully avoiding the effect of abnormal flow accumulation upstream affecting the placement of the basin boundary.

In the end, areas of low focal flow were extracted and assigned a value of one, with all other areas being assigned a value of zero. For flow direction, areas in close proximity to each other with flows pointing close to opposite directions were selected and also assigned a value of one, while the rest of the dataset was set to zero. Then, the two datasets were "added" together, and cells that produced a value of two indicated areas that were likely to be situated at a basin boundary, and all others receiving a value of zero. This new dataset was checked by comparing an overly developed stream system to the areas that were selected by the Euler maps (the new dataset). Where the areas indicated by the Euler map were clearly positioned separately from areas that showed heavy stream development, it appeared to be likely that there was a basin boundary nearby.

Most of the resultant larger basins had smaller subbasins within them that apparently could have flow traveling through them on to the basin as a whole, but would have more difficulty traveling through. For that reason, two divisions were created, one for the basin scale, and the other for the subbasin level. As discussed earlier, these two scales were then approximated using the watershed tool by setting the 100,000 cell and 1,000 scale inputs as the minimum basin or subbasin size, respectively. Using the streams produced by the watershed tool allowed for a shapefile of polygons, as well as an appropriate stream network with one outlet for each basin or subbasin, to be built automatically, instead of having to digitize these systems by hand.

Focal Flow

    -Neighborhood Analysis Focal Flow

    Input: gbj_utm

    Output: fflow

Tool 2 Dataset

-Map Algebra

"Value">=245 OR "Value"<=15

Reclassify: selection = 1, not selected = 0

Input: fflow

Output: fflowsel

Reclassify: selection = 1, not selected = 0

Input: flowa

Output: flowasel

Raster Calculator

Sumrast = flowasel + fflowsel

ID Basins and Subbasins onto Stream Segments

The gridcode of the individual basins and subbasins was imprinted onto the streams along the stretches

that they intersect with the respective basin and subbasin polygons. This operation makes it possible to

disregard the stream segments that make up the subbasin level of detail to the subbasin scale data is

not desired by selecting only line segments that have a basin level gridcode.

Identity Operation

Input 1: ws100

Input 2: st1

Output: stws

Input Operation

Input 1: ws1

Input 2: stws

Output: stbas

Producing Geometric Network from Stream Data

In order to make a geometric network, a new personal geodatabase has to be made, followed by a new empty feature class has to be built. The stream network lines must be imported into the new feature class. Also, the points from the streams must be extracted through a tool such as X-tools or the Feature Vertices to Points Command in the Data Management Tools/Feature Vertices menu of the ArcGIS Toolbox menus. After that, in ArcCatalog, a new geometric database is produced via these feature classes. When the network was built, the defaults were selected, except for allowing complex edges, and snaps being set at roughly the resolution of the cell size (in this case, 100m) was also useful. Sinks are permitted, the source of those sinks being the points extracted from the stream network.

After the network was produced, it must be edited. The lines that are not connected need to have a Union operation performed on them. The extra line segments that appear as either artifacts from raster conversion or other errors also need to be removed. The flow direction must be set by changing the ancillary role of the ultimate downstream point in the system to "sink".

If the portions of the network have too many sets of lines and points that were duplicated when the network was created, have been brought over as multipart edge features, or were in other ways corrupted, sometimes it is faster and more effective delete the old edges and to digitize new line

features (note: they must be complex edges, not simple) directly on top of the stream by snapping lines to the points of the original streams.