CHAPTER 3 – LITERATURE REVIEW

Human land use activities impose significant influences on watershed processes. It is well understood that urbanization alone can significantly alter the hydrology and sediment supply of streams (Wolman 1967; Leopold 1972; Graf 1976; Morisawa et al. 1979; Booth 1991). This literature review focuses upon investigations where parallels can be drawn with the land use changes observed in the San Pedro Creek watershed, and methods for understanding the effects of urbanization on fluvial processes.

Research into the impacts of urbanization on streams has a notable history. For some time, negative cumulative effects of human development have motivated researchers to theorize, study and evaluate these effects as they pertain to drainage systems. Early on it was proposed that:

> When an area is developed for housing or other urban purposes, the immediate hydrologic effect is to increase the area of low or zero infiltration capacity and to increase the efficiency or speed of water transmission in channels or conduits (Dunne and Leopold 1978).

Urbanization has steadily replaced open spaces and forced dramatic changes to watersheds in the process. Natural drainages have been replaced by human structures, or reengineered for human purposes.

Early Studies

Luna B. Leopold is one of the pioneers of scientific research evaluating the adverse changes humans can impose on streams. His work on the Watts Branch of the Potomac River near Rockville, Maryland is considered seminal among investigations of temporal fluvial geomorphic response to urbanization (Leopold 1973). Leopold helped to introduce the idea that urbanization is an impact on watersheds, geographic units that he considered significant environments in form and function.

William L. Graf focused on how changes in channel networks occur as a result of impervious surfaces, proposing that:

> Roofs, sidewalks, streets, parking areas, and sod lawns accelerate overland flow and restrict infiltration, resulting in flood discharges of greater magnitude and frequency than those that occurred before urbanization. In addition to changes in surfaces, however, suburban development introduces another significant change into the hydro-geomorphic systems in the form of radical alteration of channel networks (Graf 1976).

Graf's research (1976) found that an increase in impervious surface added a significant artificial channels to the previously existing natural drainage network. His early work references Leopold, among others, but is unique for its time because of its multi-variable approach. Graf examined several indicators of change and ranked the importance of their spatial relationships to the drainage network.

These two studies are significant not only for their relatively early publication but also for their uniquely geographic approaches. They helped formulate research standards and approaches that reappear in many later works.

Grazing and Farming

Grazing and farming can also result in watershed modifications and channel response. In western human landscape evolution, these two activities have often preceded urbanization. Such is the case with San Pedro Creek. Though it can be very difficult, or at times impossible, to quantify grazing's and farming's impacts separately from urbanization, it is still important to consider the influence these activities may have had on human landscape evolution and the resulting effects on watershed processes. This review only considers some of the significant effects that may have occurred in the San Pedro Creek watershed. There is an extensive body of literature on these subjects.

Grazing can result in soil compaction, soil erosion, and changes in vegetation communities and abundance. These changes to the watershed can result in reduced infiltration, increased runoff, and increased sediment supply and transport. The degree to which grazing practices can cause negative watershed impacts is directly related to the degree of over-grazing in the basin. According to Tate (1998) overgrazing occurs when the number of cattle per unit area, per unit of time exceeds the carrying capacity of the landscape. Though it is

uncertain whether over-grazing occurred historically in the San Pedro watershed, the presence of livestock is known and some level of effect can be assumed.

The presence of cattle and the trampling that ensues can lead to a compaction of subsurface soil layers while loosening surface soils (Reid 1993). Liacos (1962) found that the shallow horizon of grazed soils in Berkeley, California typically had a higher density (expressed as bulk density) than nearby ungrazed soils. Several rangeland studies have found a strong correlation between increased bulk density and water infiltration (Packer 1953, 1963; Rauzi et al. 1966). Given enough precipitation, reduced infiltration resulting from subsurface compaction will increase surface runoff's capability of eroding and transporting loosened surface sediments to nearby streams. This process may be responsible for the initiation or exacerbation of the gullies identified on the northern hill slopes of San Pedro Valley. Increased runoff also leads to increased peak discharge and more erosive instream flows (Allen-Diaz et al. 1998). Increases in peak discharge can be compounded by the concentration of flows in terracettes or "cattle tracks", as observed by Stephenson (1994).

Grazing has had a permanent impact on the grassland community of the San Pedro watershed and could have altered the riparian community as well. Burcham (1982) described how California Coast Range grasslands changed from perennial bunchgrasses to European annuals with the introduction of grazing. According to Reid (1993) changing the longevity of roots through conversion from

perennial to annual grasses can play a part in changing soil texture and surface roughness. Reid also reported that grazing could lead to decreased ground-cover density due to consumption of plants, as well as trampling. Reducing soil-binding benefits of roots, and exposing more surface area to rain-splash erosion could have generated more sediment supply to San Pedro Creek.

As for riparian impacts, cattle have been found to spend significantly more time in riparian areas than in drier upland areas (Harper et al. n.d.). Similarly, Roath and Krueger (1982) found that 81% of forage use was sustained by a riparian area that made up only 1.9% of the cattle range in an Oregon basin. Consumption of young riparian plants and trampling stream banks likely increased channel instability and erosion in San Pedro Creek.

Crop farming has also been observed to have measurable impacts on watershed processes. Common changes include increased runoff and peak discharge, increased sediment supply and channel erosion, and direct channel alteration. Farming occurred for approximately 170 years in the San Pedro Creek Watershed, peaking between the late nineteenth and mid twentieth centuries. During this later period, all of the level valley areas had been converted to farms.

Converting land to agricultural use has often meant draining wetlands and extirpation of the native vegetation community (Reid 1993). In the Willamette Valley, Oregon, for example, the natural drainage network of bayous and

floodplain channels were drained and confined into a single channel to increase arable land (Sedell and Froggatt 1984). This conversion typically initiates processes resulting in other direct and indirect impacts.

Plowing can reduce soil compaction near the surface (Voorheese 1983) while subsurface compaction increases (Blake et al. 1976). Surface compaction can also increase where roads and other agricultural service areas are established (Reid 1993). This change in the earth surface, along with appurtenant drainage and irrigation facilities, leads to increases in runoff and peak discharge in streams. In a study reported by Dunne and Leopold (1978), overland flow resulting from saturation developed more frequently on soils used for growing crops. Similarly, but throughout a larger study area, Knox (1977) observed that conversion from natural vegetation to crops led to an increase in flood magnitudes in several watersheds.

Exposed soils and increased surface roughness results in greater sediment supply to streams when overland flow occurs (Reid 1993, Woltemade 1994). Woltemade (1994) found that sediment eroded from upland farms in the Grant River in southern Wisconsin were deposited as overbank levees in the lower river reaches. Knox (1977) who observed this same phenomenon in the Platte River found that raised channel banks concentrated discharge and increased stream power within the channel. Increased downstream erosion caused upstream reaches to incise and peak discharges to increase up to five

times pre-settlement levels. Woltemade (1994) showed that 33 out of 69 upstream locations in agricultural areas had incised enough to containe the 10-year frequency flood. Of these sites, almost half could contain a 25-year frequency flood. Knox (1989) summarized this process:

> The enlarged channels now contain most floods that once overflowed stream banks, and because these channels perform a "flume-like" function with relatively little hydraulic roughness compared to that experienced when shallow flood waters are spread across wide floodplains, the floods are quickly routed downstream with considerable velocity and erosive force… (Knox 1989).

Intentional channel straightening typically shortens the stream channel by cutting off natural meanders. This is often done to maximize land for crops, as occurred throughout San Pedro Creek (Collins 2001). Yet the channel length of lower San Pedro Creek was actually increased by approximately 0.8 mile (1.3 km) with the ditching and draining of the lake and surrounding marsh creating a discrete channel where no channel had existed (Collins 2001). In either case, channel slope is steepened, causing an increase in erosive flows and channel incision. Emerson (1971) studied the channelized Blackwater River in Missouri and found that the channel had been incising for 60 years with no sign of stabilizing. According to Dunne and Leopold (1978) the change of a rivers slope can cause a long-term, irreversible condition of instability that may be the most difficult impact to correct without significant effort.

Urbanization

Perhaps the most obvious landscape-level change to accompany urbanization is the extent to which previously natural surfaces are covered by engineered, impervious ones (May 1997). Once vegetation and soils are replaced with buildings and paved surfaces, the infiltration potential for precipitation is greatly reduced, resulting in increased runoff, decreased lag time and increased peak discharge in streams. Sediment source areas and supply dynamics are modified when impervious areas cover the natural earth. Increased peak discharge and reduced sediment supply often result in accelerated erosion leading to increased aggradation in depositional zones. These effects have generated negative impacts on fluvial geomorphic processes, riparian habitat, and water quality, leading many researchers to investigate and improve our understanding of how urbanization alters streams.

Impervious Surface Area

Impervious surfaces associated with urbanization include roads, sidewalks, parking lots, and buildings- any artificial, hardened surface that reduces permeability and infiltration of water into the soil (Arnold and Gibbons 1996). A study in the Puget Sound region of Washington (1994) indicated that approximately 60% of the impervious cover in a suburban area was related to

transportation (City of Olympia 1994). Schueler (1994) described impervious surface area as a good indicator of development that can be used to characterize the current state of water quality and biological diversity of a stream. He developed categories of stream condition in terms of beneficial uses and impervious area. As shown in Figure 6, watersheds with 10% or less cover are considered sensitive, 11% to 25% are considered impacted and anything above 26% impervious cover is a non-supporting creek.

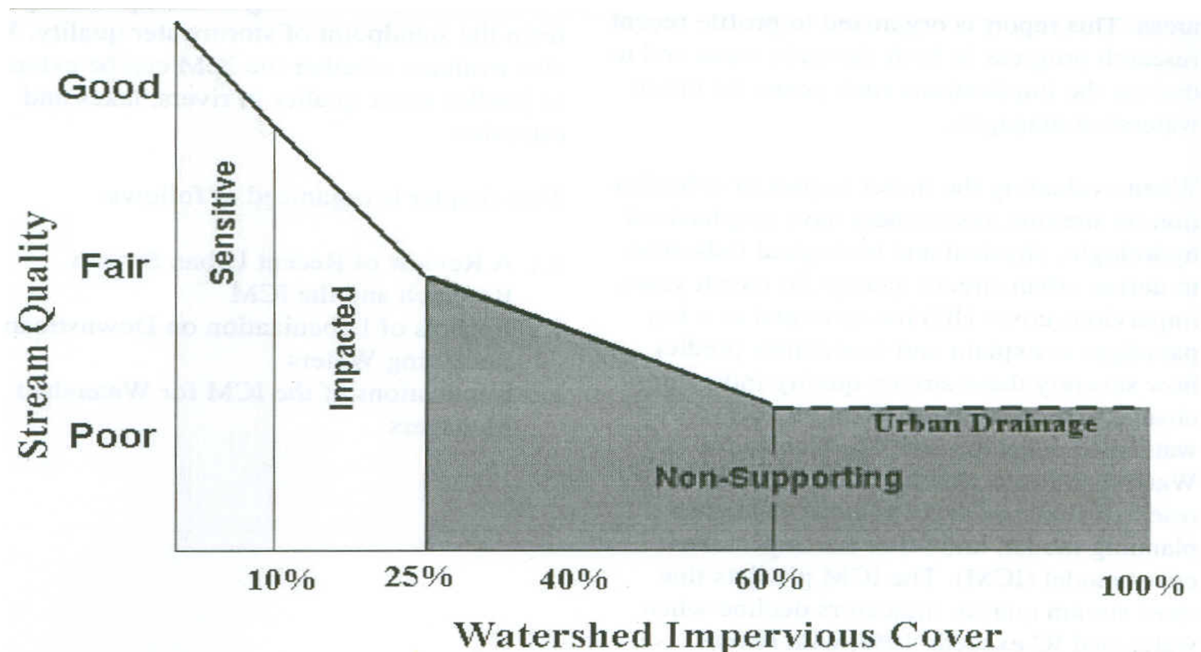

Figure 6. Impacts of Impervious Cover. Center for Watershed Protection, 2003:2

The location and connectivity of impervious cover to the receiving water body is also significant. Boyd, Bufill, and Knee (1994) defined the impervious area draining directly to the natural drainage system as the “effective impervious

area”. They distinguished drainage pathways, observing that “connected” impervious areas drain directly to the natural drainage system, while “unconnected” impervious areas drain to pervious areas. For example, a street draining to a stormdrain system that flows to a creek is “connected”, while a school yard that drains to the surrounding playfields is “unconnected”. Impervious areas that are unconnected can still contribute to runoff when the surrounding pervious areas become saturated. Leopold (1991) reported a significant increase in runoff in Cerrito Creek, Berkeley, California due to saturated overland flow, implying that the pervious areas could become effectively impervious.

Investigations of Boyd, Bufill, and Knee (1993) observed a high degree of effective impervious area in 26 urban basins in Canberra, Australia. They plotted total storm rainfall depth against runoff depth for a range of storm events and found that the effective impervious area remained fairly constant for all storms, plotting as a straight line with minimal scatter from pervious area contribution. Conversely, Stephenson (1994) found that 70% of the 25% impervious area found in developments near Johannesburg, South Africa was unconnected, so the effective impervious area was considerably less prior to saturation.

In addition to causing changes in drainage surfaces, urbanization may radically alter channel networks. Graf (1976) focused on how changes in channel networks occur as a result of impervious surfaces, proposing that roofs,

sidewalks, streets, parking areas, and even sod lawns accelerate overland flow and restrict infiltration, resulting in flood discharges of greater magnitude and frequency than those that occurred before urbanization. At the same time, Graf described how an increase in impervious surface increases the length of artificial channels to the previous network of natural channels. An increase in channel network results in higher drainage density, defined as the length of the drainage network divided by the drainage area (Dunne and Leopold 1978). Graf (1977) described changes to a drainage network in a developing area near Iowa City, Iowa, including a 50% increase in drainage density due to artificial channels. Dunne and Leopold (1978) found that high drainage density commonly result in high peak flows due to more efficient capture and transport of runoff. May (1997) measured artificial and natural drainage density in watersheds of the Puget Sound ecoregion in Washington and used the ratio of artificial to natural as an indicator of urban impact.

Runoff

Elements that control runoff include frequency and intensity of rainfall, and ground infiltration potential which is in turn controlled by soil type, soil moisture, antecedent rainfall, surface cover type, percentage of impervious surfaces and surface retention. Travel time is determined by slope, the length of the flow path, the depth of flow and surface roughness. These elements in different

combinations result in variations in peak discharge values. Other significant factors include the size of the watershed, the location and size of a development, and the distribution and intensity of rain events (Cronshey 1986). When a portion of a watershed is urbanized, some of these controlling factors are altered to the point of having a significant influence on runoff. Generally speaking, surface cover type, surface retention, length of flow path, and surface roughness are most affected, resulting in increased runoff reaching the natural drainage channel in less time.

Replacing native soils and vegetation with engineered, impervious surfaces has been clearly linked to increases in the amount of runoff that is generated during rainfall events. Schueler (1994) for example, compared the runoff of a parking lot with runoff of a meadow and found that the parking lot produced more than 15 times the runoff of the meadow. On a larger spatial scale, Schueler (1987) compiled runoff data from 44 small urban catchments across the United States and found that runoff increases were directly related to amount of impervious cover. In his comparative study of an urbanized watershed with one that was grassland dominated, Stephenson (1994) observed that total surface runoff from the urbanized drainage was four times greater than from the grasslands.

Urbanization also has a measurable effect on the runoff rates in a watershed, which can be expressed as *lag time*, or the time period between a

burst of rainfall and the resulting hydrograph downstream (Leopold 1991). A hydrograph plots discharge over time at a specific point in a stream (Dunne and Leopold 1978). When rain falls on urbanized regions, smooth impervious surfaces cause immediate runoff that in turn flows through engineered drainage systems, resulting in reduced lag time. Two ways of measuring lag time are lag-to-peak, which is the time between the center of mass of rainfall and the peak of the hydrograph, and centroid lag which is the time between the center of mass of rainfall and the center of mass of the resulting hydrograph (Leopold 1991). Lag time is an important hydrologic measurement that describes the response of a watershed to rain. Leopold (1991) described the measurement of lag time as a better expression of the degree of urban landscape alteration than the direct measure of impervious cover. Lag time can also be influenced by antecedent wetness, or the amount of water already contained in pervious surfaces. As described earlier, when otherwise pervious surfaces become saturated, or close to saturation, they can produce rapid runoff much like an artificial impervious surface.

Peak discharge, a measurement or predictor of the highest discharge during a specific rain event or specific period of time, is linked directly to runoff and lag time. Compiled data from Carter (1961) indicate that an area that has been urbanized might show an increase in peak discharge of from 2 to 6 times the pre-urban conditions. Later work by Hollis (1975) compiled peak discharge

data from fifteen studies, which showed a relationship of increasing peak discharge with increasing impervious surface area and decreasing storm magnitude. Neller (1988) also reviewed data from several studies and found that small floods may increase 10-fold due to urbanization. In his work in King County, Washington, Booth (1990) found a two- to three-fold increase in peak flows in typical low-density urban areas with 10-20 % impervious cover. Leopold (1978) compiled data from seven different studies, concluding that a 20 % increase in impervious surface area generated enough runoff to double the frequency of bankfull flows. These results were consistent with his findings in the Watts Branch where urbanization led to an increase of more than two-fold for flows with a recurrence interval of 1.5 to 5 years (Leopold 1972).

These works are only a few among many demonstrating that reduced infiltration from impervious surfaces is directly related to the amount of runoff that eventually flows to nearby water bodies. In the case of San Pedro Creek, the North Fork, and a significant percentage of the flatlands have experienced dramatic increases in the percentage of impervious surface area since the onset of urbanization in the early 1950s.

Sediment

Urbanization also affects the sediment supply of a stream, often in cycles. Wolman (1967) described three stages; 1) an initial state of equilibrium in which

the watershed is primarily agricultural or forested, 2) the construction period which exposes land to erosion and increased sediment supply, and 3) the final stage consisting of an urbanized landscape which reduces sediment supply by increasing impervious surfaces. Figure 7 illustrates these stages.

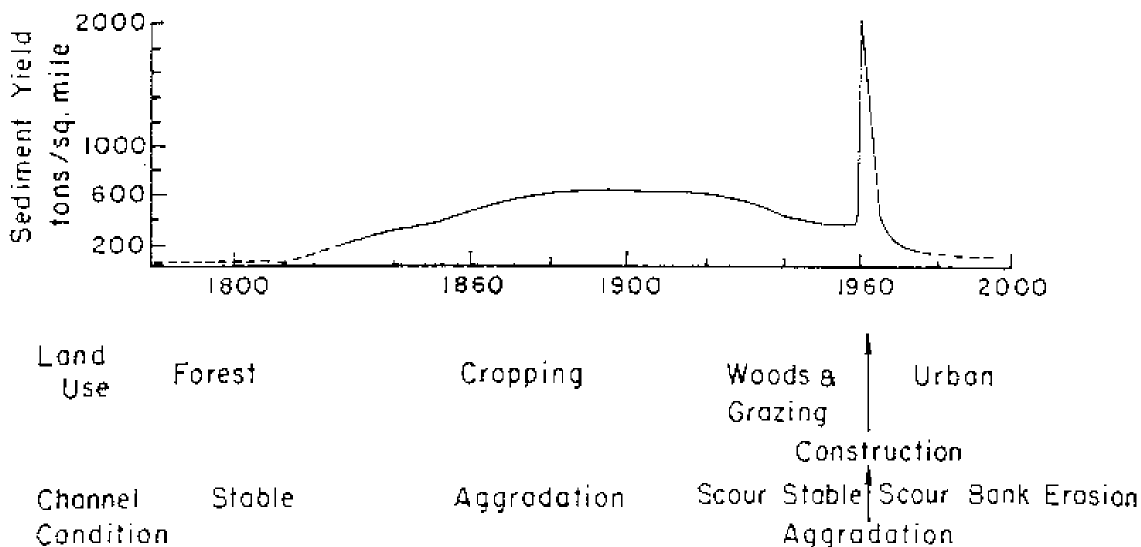

Figure 7. Land Use and Sediment Yield. Wolman, 1967

Parts of the San Pedro Watershed have experienced this same cycle, though the initial stage of equilibrium is thought to have preceded the agricultural stage, which is assumed to have caused an increased sediment supply. Leopold (1972) agreed with Wolman finding that sediment concentrations increased during the

construction phase (second stage) followed by a decrease after buildings and paved roads were finished (third stage). It should be noted that modern developments, unlike those in San Pedro Valley or observed by Leopold and Wolman, are legally obligated to comply with the Federal Clean Water Act of 1972 which requires permits and best management practices designed to protect streams and other water bodies of the United States from pollution. Though not infallible, this protection does include measures for preventing increased sediment supply to streams from construction sites.

Leopold's efforts to quantify channel change over time measured cross-sections in the Watts Branch between 1953 and 1970 and found a decrease in cross-sectional area of 32% (Leopold 1994) due to “plastering” of excess silt onto the channel banks. This loss corresponded with rapid development in the basin. Wolman indicated that sediment yields from areas subject to construction might be several hundred times that of forested lands and grazed areas, or several times that of agricultural areas. He also reported data from Keller (1962) who found sediment concentrations in channel discharge to be 3 to 5 times greater in a watershed under construction when compared to a rural stream.

Following the construction stage, impervious surfaces cover previously exposed soils and vegetation, and pipes and lined ditches replace a portion of the drainage network. These changes reduce the amount of sediment available for transport to and through the natural stream network. The North Fork and the

greater San Pedro Watershed, with the exception of an occasional minor construction project, are built out and any major developments in the future are prevented by the dedication of protected open space.

Literature reporting sediment concentrations following construction are not as available as for sediment concentrations following other land use impacts. Wolman (1967) did compare three watershed conditions on two streams representing pre-development, active construction, and post-development. He found that suspended solids in the post-development stream reach were lower than the pre-development reach 85% of the time and that active construction concentrations were 5 times greater than pre-development. Wolman also surveyed fourteen stormwater outfalls draining urban areas. Of these facilities, only three showed sediment accumulation of 20% or more and of these, two were draining developments that had just been constructed a year prior to observation. Where development had been complete for five or more years, sediment accumulation only filled 10% or less of the outfall cross-section. Wolman's work supported the assertion that sediment yields during construction are greater than pre-development and agricultural conditions, and suggested that post-development conditions led to very low sediment yields equal to or less than those from forested lands.

Fluvial Geomorphic Response

Stream channels will respond to alterations of the hydrologic and sediment regimes that maintained the pre-disturbance equilibrium state. According to Wolman (1967):

> Upon completion of streets and sewerage systems sediment derived from the watershed decreases while the rapidity of runoff is increased. Channel bars and vegetation may be removed by flows of clear water. At the same time the absence of a fresh supply of sediment may result in progressive channel erosion without concomitant deposition.

As suggested by Wolman, typical fluvial geomorphic responses include channel incision, and bank erosion. These adjustments occur as a result of increased frequency and duration of peak flows exposing the channel to increased shear stress that exceeds the critical threshold needed to move bank and bed sediments (Schueler et al. 2003). These conditions are further exacerbated by an absence of sediment supply from outside the channel boundary.

During periods of adjustment following urbanization, receiving channel cross-sections can increase in both width and depth (Wolman 1967; Morisawa 1979; Booth 1990; and Pizzuto et al. 2000). Several studies compiled by Schueler (2003) found that channel enlargement in response to urbanization can result in cross-sectional area that is 2 to 8 times greater than pre-urbanization conditions. Gregory (1992) observed channel capacity increases in the Monks

Brook in southern England on the order of 2 to 2.5 times after urbanization. Channel adjustments resulted in width increases up to 2.2 times and bed incision up to 0.4 meters. Morisawa (1979) found that streams in several urbanized drainages in the Pittsburgh, Pennsylvania area were enlarging by incision, bank erosion, or both and attributed variations in enlargement to the complex interactions of hydrology and differing resistance of bed and bank material to erosion. Channels with more resistant bed material will erode laterally while channels with more resistant banks will tend to incise. Booth (1990) indicated that the immediate increase in discharge may, with time, cause an increase in stream channel cross-sectional area or potentially catastrophic channel incision depending on slope and geology.

Channels can yield significant amounts of sediment from bank erosion and bed incision, especially when they are in an unstable state. Trimble (1997) hypothesized that 60% to 75% of the sediment yield from watersheds he observed in California and Texas was derived from bank erosion. Collins (2001) reported that within the 2.6-mile (4.2 km) study reach of San Pedro Creek, sediment supplied from bed incision was 7 times greater than from bank erosion. Significant instream erosion may continue until development of the watershed has stopped long enough for the channel to adjust to a more stable geometry suited to post-urbanization flow and sediment regimes. Morisawa (1979) and Ebisemiju (1989) suggested that once development ceased, the stream channel

would adjust to the post-urbanization flow and sediment regime resulting in a new equilibrium state. Finkenbine (2000) observed these conditions in Vancouver streams that stabilized 20 years following completion of construction.

Impacts of Urbanization

Urbanization has many negative impacts on many aspects of watersheds. May (1997) conducted studies in the Pacific Northwest and found that urbanization changed the physical, chemical, and biological characteristics of streams. Matuk, 2001 reviewed the impacts of urbanization on water quality in San Pedro Creek. For the purposes of this study, a brief review is provided for work related to physical channel impacts that occur as a result of increased impervious surface area.

When urbanization results in bank erosion, bed incision or both, alterations in stream channel geometry can be significant. Impacts associated with these alterations are often defined by the boundary conditions of the affected reaches. Ferguson (1991) explained:

> Such accelerated lowering and bank erosion can cause destruction of aquatic habitat; excavation or dewatering of riparian zones; undercutting of structures, such as buildings and bridges; and loss of streamside yards, gardens, trees, parks, open spaces, and mature riparian vegetation.

Schueler (1992) emphasized impacts to riparian and instream habitat. Erosion destabilizes riparian vegetation on channel banks, while sand and silt deposits

smother streambed habitat features. Alteration of riparian and instream channel habitats threatens dependent species such as salmonids (May 1997). Pools, riffles, and gravel beds critical to aquatic fauna are scoured by increased shear forces or smothered by increased fine sediments from bank erosion. Increased fines could be correlated with decreased aquatic species health (May et al. 1997). Loss of riparian vegetation from undercut and eroding banks reduces cover, reducing water temperature in winter and increasing it in the summer (Galli 1991). Reproduction and survival of aquatic species are compromised.

Stream bank erosion and loss, or potential loss of property leads public and private entities to respond with channel armoring projects that often include riprap, gabions, concrete, or some other sterile material. Channel armoring reduces habitat potential and transfers accelerated velocity vectors to downstream banks. Sauer (1983) observed that channel armoring influenced peak discharge rates, increased the efficiency of instream runoff transport, and amplified shear stress velocities and channel erosion. Collins (2001) identified various types of revetment covering 20% of the length of the main stem of San Pedro Creek. An additional 37% of the bank length was considered to be actively eroding and potentially subject to new revetment projects.

Research Methods

Interest in measuring the effects of urbanization on streams and the complexities inherent in watershed systems has produced a variety of research methods. Because watershed processes are controlled by several variables, an oversimplified approach is at serious risk of missing important information. A clear understanding of the physical and human characteristics of a given watershed is critical if a method is expected to produce valuable results.

Ebisemiju (1989b) describes four widely recognized methods for identifying changes in stream channels. He associates these techniques with relevant works of specific authors: the deductive method comparing pre- and post disturbance conditions (Wolman 1967), the monitoring of channel cross sections at established sites over time (Leopold 1973), the regime theory involving the comparison of relationships between channel form, water discharge and sediment yield (Schumm 1969; Rango 1970; and Blench 1972), and the spatial interpolation technique involving the comparison of a modified stream with an adjacent "natural" stream or the comparison of an unaffected reach with a modified reach on a single stream (Hammer 1972; Gregory et al. 1976; and Park 1978a). Gregory, Davis and Downs (1992) add that the most common "historical" method for identifying channel change is the comparison of historical large-scale maps and remotely sensed data with current data to establish modifications in

channel planform. The cross-sectional, regime theory, and spatial interpolation methods are discussed further because of their relevance to this study.

The cross sectional monitoring approach conducted by Leopold, involved measurement of 14 cross sections of a stream channel about every other year for 20-years (1953-1972). Changes in cross sectional area were compared to ascertain changes in channel size resulting from erosion and deposition attributed to increased flood frequency relative to urbanization in the watershed (Loepold 1973). Results of some of the years are represented in Figure 8.

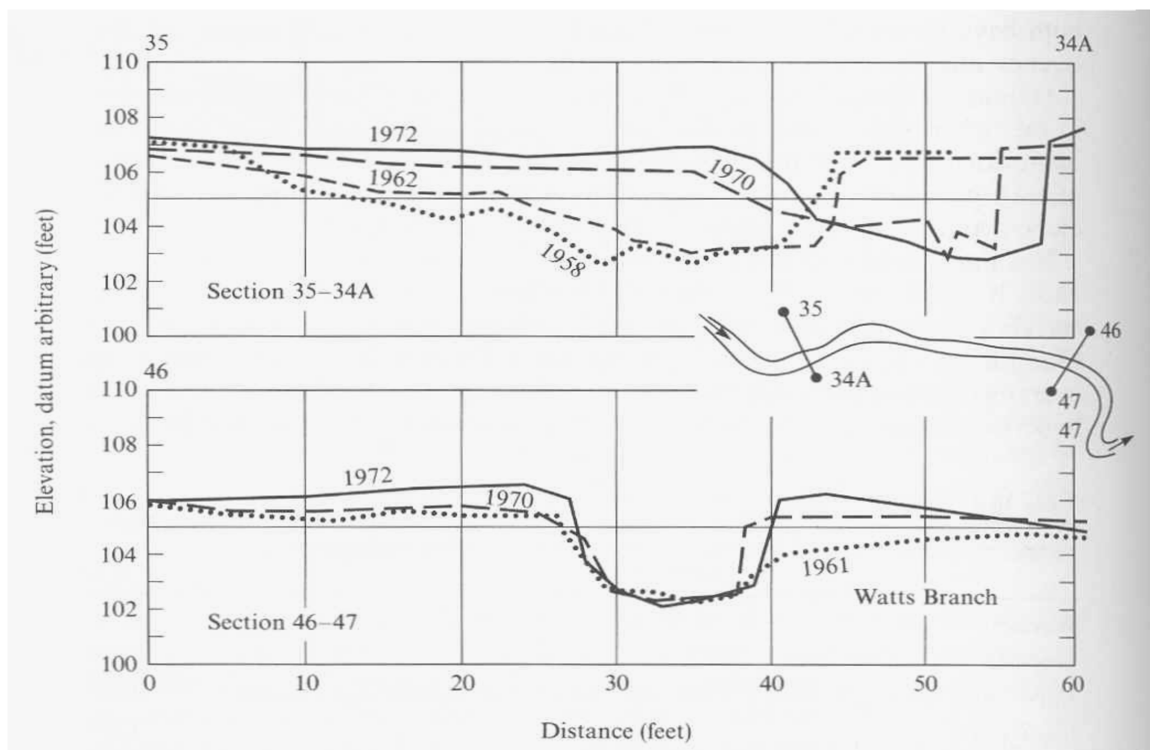

Figure 8. Watts Branch Cross-Sections. Dunne and Leopold, 1978:698

It is impractical for most researchers to collect cross sectional data over twenty years, and the effectiveness of this method is strongly correlated with length of time measured, but even on a shorter time scale one can observe localized or systematic changes in the channel form.

Beyond comparing the changes in cross sections, Leopold utilized the regime method by calculating lag time and comparing it to precipitation data, drainage size, drainage density, discharge, sediment yield, increased urbanization and changes in stream channel geometry. These methods became standard practice, aiding researchers in determining the response of a channel to urbanization and other land use changes.

In a study designed to indicate the irregularity of stream response to urbanization in a humid tropical basin, Odemerho (1992) employed the spatial interpolation technique to measure whether downstream propagation of influences from urban land use was detectable (Odemerho 1992). Odemerho set up ten stations along the Ikpoba River in Nigeria for the purpose of measuring changes in the bankfull channel cross-section. He placed the stations upstream, adjacent to, and downstream from the urbanized area and monitored changes in channel depth and width finding that channel dimensions varied with different proximity to the urban area. Upstream, increasing drainage area corresponded with larger cross-sections until reaching the urban section, which was constricted

by sedimentation from urban inputs. He then interpreted the changes in channel dimensions to determine the impact of urbanization.

Like Odemerho, Ebisemiju (1989b) used the spatial interpolation method to measure channel geometry in developed and undeveloped drainages. Different from Odemerho, Ebisemiju distributed measuring sites in seven urbanized and six natural headwater catchments throughout the Elemi and Ireje watersheds, also in Nigeria. Ebisemiju also found that channel cross-sections in and downstream of urban areas were reduced by sedimentation and noted that the model of urban induced erosion and incision proposed by Morisawa (1967) may not be appropriate in the humid tropics.

To better understand the changes that resulted from development, Gregory, Davis and Downs relied on the comparisons of large-scale (1:2500) topographic maps. By examining stream reaches on maps produced in different years, they could trace the changes in channel width and channelization that resulted from urbanization. They cited Gregory and Brooks (1983 and 1992) who used large-scale maps from different dates to measure increases in channel width downstream of bridges.

Close attention must also be paid to the location of urbanization in a watershed and how different spatial relationships with the stream can result in different responses of the stream channel. In a study of the impacts of urbanization in Nigeria, Ebisemiju (1989a) hypothesized that:

> The location of urbanization in a watershed should influence the magnitude of runoff and sediment delivered to a stream from urban surfaces during rainstorms of comparable intensity, duration and erosivity. It should also influence variations in peak-flow discharges and stream velocity along a channel…

It has been shown that the placement of the urbanized area within a watershed can result in different effects on the stream. This has become a widely accepted precept that should be considered regardless of what method the researcher is using.

The methods discussed above represent only four of the many methods that exist for determining the changes in a watershed due to human development. Computer modeling and manipulation of digital information present two examples (not discussed here) of advancing methods that will continue to provide better datasets for both comparative and non-comparative studies. Several of the methods have been rigorously tested over time, both in the field and on the computer, and all of them have potential for refinement and improvement. Based on the literature, however, it is clear that the best research will employ a combination of methods well suited to the individual study.

Proposed Solutions

In order to frame any discussion of mitigating and ultimately avoiding the potential impacts of urbanization on streams, it is necessary to understand what has been sacrificed, what will be saved and why it is important.

> To define our goals in watershed management requires first that we articulate the values we associate with watersheds and the stream channel network. These values include the function of the natural stream-and-floodplain network in flood runoff and drainage in general, the ecological values of the aquatic and riparian systems, and the recreational and aesthetic values of these systems. Urbanization affects all these, but they can all be managed for (Kondolf et. al 1991).

Several possibilities have been suggested for avoiding degradational urban influences on streams as well as the potential catastrophic and economic influences of streams on urbanization. At the same time, limited suggestions are given for after-the-fact repairs, perhaps due to economic barriers and the potential for negative environmental impacts resulting from the current dependence on engineered solutions. Methods most commonly suggested in the reviewed literature can be divided into two categories: better land use planning and continued research aimed at a clearer understanding of the watershed as a natural system and an urban-nature interface.

Kondolf recognized the necessity of identifying the channel-floodplain prior to the consideration of development in the valley bottom. He suggested the use

of historical records to indicate previous stream migrations and areas of flood inundation (Kondolf et al. 1991). By understanding the natural floodplain and avoiding it as an area of "prime real-estate" both the channel and development can be more successful.

When the floodplain is not preserved, the changes in urbanized streams often lead to unattractive and even dangerous conditions due to increased flows, flooding and environmental degradation. As a result, channels are paved, fenced off and made unavailable or undesirable to the public and dependent wildlife. In this way, streams become "invisible" when they should be valued aesthetically, recreationally and as habitat.

As an alternative, planners should consider the design of streamside parks as uses that can be flooded with less cost to humans. Such parks could also reduce the potential for flooding downstream and provide areas of beneficial use for people and wildlife (Dunne and Leopold 1978). Odemerho (1992) speculated that:

> The development of green belts/lawns and other options that encourage infiltration in urban areas will be more successful than development of storm sewers both because of capital constraints and the need to reduce rapid flows into the existing river channel.

He suggested this as a method of reducing flows downstream from the development and as a long-range strategy for stream channel stability and downstream impact mitigation.

When a development is already complete, the community and planner must employ measures that recognize areas sensitive to flooding and channel instability. Booth's study in King County, Washington (1990) led him to believe that "[f]low diversion, piping, adequate detention, or extensive upland infiltration buffers…" are all possible proactive solutions to problem areas that may not have been adequately considered before planning and construction.

Research-based solutions are suggested to provide necessary data to support proper land use decisions. Investigations in and away from the field must focus not only on the location of the floodplain but also on the location of change and amount of change expected. Much of the literature indicates that alterations due to human influence may be varied and spatially discontinuous. Consequently, it is essential that successive studies identify the location of stream channel responses to aid in developing proper avoidance measures (Gregory et. al 1992). Ebisemiju also suggests giving more attention to the pattern of stream response to urbanization (Ebisemiju 1989b).

Finally, Luna Leopold cites a need for closer study and better understanding of small drainage basins. "The land planner may be interested in the hydrologic effects in a basin the size of a housing development or even a

single house" (Leopold 1991). It has become common practice to place developments in smaller valleys as large-scale development sites have been built out. By understanding the hydrology of small basins in varying environments, the land planner will be better equipped to avoid serious problems. By estimating natural lag time and projecting post-urbanization lag time, planners can better design to avoid hydrologic impacts or "hydromodification" to streams and protect from flooding to the community.