ABSTRACT

PIERPONT, LAUREL HUGHES. Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Pre-development Flow Regime. (Under the direction of Dr. E. Downey Brill).

The modification of land and water resources for human use alters the natural hydrologic flow regime of a downstream receiving body of water. The natural flow regime is essential for sustaining biotic structure and equilibrium within the ecosystem. A typical approach to achieve a hydrologically friendly development is to locate and design stormwater control structures, or Best Management Practices (BMPs), to match peak and minimum flows for design storms. A more aggressive strategy for environmentally sustainable development would ensure that there is no difference between pre- and post-development flow regimes for all storms and at all times through the design of development strategies that maintain the natural flow regime under post-development conditions at the watershed outlet. Many sub-catchments contribute to the composite flow at the watershed outlet of a large watershed, and at each of these sub-catchments, the flow regime may be altered, though the flow regime is maintained at the larger watershed level.

This study uses a simulation-optimization modeling framework to analyze a hydrologic metric that represents the total degree of hydrologic alteration for a given development pattern. The objective is to minimize the hydrologic alteration by iteratively updating and modifying the development pattern in the watershed subject to maintaining some pre-defined minimum level of total development. Thirty-three hydrologic indices are used to characterize variation in the flow regime and are represented as one value indicating the hydrologic alteration for that development scenario. Continuous simulation of urban runoff is executed by the Stormwater Management Model (SWMM). Two optimization techniques, Nelder Meade (NM) and Genetic Algorithm (GA), are applied to the watershed as separate search techniques and then combined into a hybrid approach to investigate the methodology. Comparison of the solutions yields a distinct trade-off between total land developed and degree of hydrologic alteration. Results of this study present numerous solutions that are similar from the standpoint of hydrologic alteration, but dramatically different in terms of development pattern.

Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Pre-development Flow Regime.

by
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DEDICATION

"When one tugs at a single thing in nature, he finds it attached

to the rest of the world."

- John Muir

This work is dedicated

to the love of my life;

to my family;

and to all the people who have inspired me along the way,

Thank you!

BIOGRAPHY

Laurel Pierpont was born and raised in New England. She graduated from Brown University, in Providence, RI, with an honors Sc.B degree in Environmental Science. Her undergraduate thesis: ***Examination of Possible Hydrodynamic Controls on Bacteria Concentrations in the Runnins River***, analyzed the relationships between streamflow and tidal dynamics with fluctuating bacteria concentrations. After college, she worked for an environmental consulting firm performing soil and groundwater sampling, wetland delineation, stormwater management practices assessment, and petroleum remediation. She enrolled in the graduate program at North Carolina State University in the Civil and Environmental Engineering Department in the summer of 2006. Her intent is to continue as a steward of the environment and an active participant in the management and conservation of water resources.

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CHAPTER 1: Introduction

A goal of sustainable watershed development is to maintain and preserve the natural resources and processes that create and maintain an ecosystem's diversity and integrity. Recent studies have shown a high degree of correlation between alterations in hydrologic flows and ecological and habitat attributes. As flows are easily and commonly measured and modeled, using hydrologic alterations as a basis for watershed management provides a promising direction to achieving sustainable development. Also, in many cases, pre-development flows have been measured and are available, thus enabling the definition of metrics that represent the departure from predevelopment conditions—a proper notion of sustainability.

This research defines a new hydrologic alteration metric for evaluating futuristic development scenarios. Through the implementation of an integrated decision analytic framework using mathematical modeling and optimization techniques this research has identified a method to obtain efficient development configurations and watershed development plans that preserve the notions of environmental sustainability. In addition, this research has applied, tested, and demonstrated the methodology for a realistic watershed management case study, and addressed several imminent and pertinent questions related to watershed management.

CHAPTER 2: A Method for Mimicking the Predevelopment Flow Regime

2.1 Introduction

An appropriate metric for achieving sustainable development is embedded within the mechanistic link between the hydrologic flow regime and ecosystem health. Analysis of a long term record of pre-development flows would reveal a natural variability in the streamflow dataset. This natural tendency of fluctuation is a statistically significant aspect of the streamflow record. Variation of this flow regime due to watershed development, or other manipulations such as dams, can generate a shift or change in the natural variability of the streamflow. Success in mimicking the pre-development flow regime under post-development scenarios is therefore an essential step in achieving sustainable development and conserving ecosystem health.

The development of civil infrastructure and urbanization impacts the health of a watershed and impairs receiving water bodies through the transport of pollutants through increased volumes of stormwater runoff (Klein 1997, Steedman 1988, Morley 2000). The concentration of sediments and nutrients entering receiving waterways in addition to the quantity of flow influences ecosystem dynamics (Resh et. al 1988). Modifications of hydrologic regimes can indirectly alter the composition, structure, or function of aquatic, riparian and wetland ecosystems through their impacts on physical habitat characteristics, including water temperature, oxygen content, water chemistry, and substrate particle sizes (Stanford & Ward 1979; Ward & Stanford 1983, 1989; Bain et al. 1988; Lillehammer & Saltveit 1984; Rood and Mahoney 1990; Dynesius & Nilsson 1994). Varying flow parameters such as magnitude, rate, and frequency can concentrate in-stream pollutant loads, or simply offset ecosystem function due to varying hydrodynamics, leading to various degrees of ecological degradation (Carpenter et. al 1998, Baron et. al 2002, 2003, and Allan 2004). Studies have shown that the dynamics of ecosystem function and structure depend on this natural variability of the flow regime, thereby making it a good indicator of riverine health, (Poff and Allan 1995, Richter et al., 1997).

The methodology presented in this research to achieve sustainable development by mimicking the predevelopment flow regime involves many different components. The first main component is the discussion of relevant literature and background information on the definition of ecologically relevant metrics. From this review, the main methodology for establishing the hydrologic alteration evaluator metric is formed and presented. In addition, the hydrologic simulation of modeled futuristic scenarios of development, a key step in the methodology of mimicking the predevelopment flow regime, is also discussed.

2.2 Background Information

The first generation of methods based on flow quantity for evaluating ecosystem health originated from a conference of The American Fisheries Society in 1976 (Orsborn and Allman 1976). Most of these methods focused on minimum and optimal flow requirements for target species. Methodology evolved from this point to incorporate the notion of natural flow variability. The idea that the complex assemblage of species and ecosystem function adapt to the natural flow regime and its variability led the way for establishing an index of ecological quality on the basis of flow regime targets (Biggs et al 1990). Development of these flow regime parameters involved several studies including Clausen and Biggs (1997;1998); who identified hydrologic indices with relevance to invertebrate ecology, Mader et al (1997), who also developed ecology-related classifications for flow parameters, and Puckridge et al (1998), who devised 23 hydrological measures based on aspects of flow variability in relation to fish biology.

A study conducted by Bragg et al (2005) synthesized evidence for linkage between ecological quality and flow regime parameters that could be used as a basis for characterizing environmental impacts (Table 1). For example, Hendry and Cragg-Hine (1996) report that high durations of low flow causes mortality of salmon due to elevated water temperature and deoxygenation. Other findings by DeBrey and Lockwood (1990) related high spring discharge to severe reductions in abundance and diversity of aquatic insects. Changes in phytoplankton and associated zooplankton communities were strongly correlated with declining flows as reported by Russe and Love (1997), Kobayashi et al (1998), Vierira et al (1998), and Wilby et al (1998). Thus, flow parameters, as abundantly evident in research literature and practice (e.g., Sparks 1995, Walker et al 1995, Poff et al 1997), can be used as a basis for evaluating the degree of impairment (Table 2).

Table 1 : Linkage Between Flow Parameters and Ecological Attributes (source Bragg et al 2005).

Effects	Description	Literature Sources
Declining flow	Ranunculus cover positively, and abundance of filamentous algae negatively, correlated with flow velocity. Also changes in phytoplankton and the associated zooplankton communities.	Ruse and Love (1997) Kobayashi et al. (1998) Vieira et al. (1998) Wilby et al. (1998)
Low flow	Early migration and shortened travel times observed for salmonid fish.	Quinn et al. (1997) Wallace and Collins (1997)
	Access of fish to their spawning grounds impeded or prevented. On the other hand, some species select spawning sites with low current velocity.	Duffy (1996) Hendry and Cragg-Hine (1996) Keckeis et al. (1997) Moir et al. (1998)
	Mortality of salmon due to elevated water temperature and deoxygenation; also reduced reproductive success due to stranding, dewatering and freezing of redds.	Hendry and Cragg-Hine (1996)
Prolonged low flow	Loss of salmon spawning areas, juvenile rearing habitat and 'living room'. Adult fish fail to enter the river	Hendry and Cragg-Hine (1996)
	Influx of sulphate-rich saline groundwater to the river, triggering a chain of events leading to development of a cyanobacterial bloom.	Donnelly et al. (1997)
	Very low constant flow (below natural low flow) may severely reduce wetted area and hence the overall productivity of the river.	Gustard et al. (1987)
Low winter flow	Macrophyte mortality due to frost exposure (in Norway, nuisance lotic vegetation can be controlled by draining rivers in winter).	Rorslett and Johansen (1996)
Flow cessation	Positive selection for invertebrate species that can survive in pools and under rocks.	Gustard et al. (1987)
	Silting and fen formation on floodplain that is cut off from the main channel.	Girel and Manneville (1998)
Alternating decline and increase in flow	Reversible development of submerged and floating-leaved aquatic plants in channel borders and backwaters.	Theilling et al. (1996)
Increase in flow	Decline of macrophytes as current velocity rises from 0.01 to 0.1ms□1, and loss of submerged species by scouring under abnormally high flow conditions.	Brierley et al. (1989) Chambers et al. (1991) Rorslett and Johansen (1996)
Flooding of Riparian Buffers	Increase in phytoplankton production. Decline in abundance of nonplanktonic algae and density of emergent macrophytes. Loss of aquatic vegetation due to persistent high water, sedimentation, and associated resuspension of sediments which in turn impedes light penetration.	Robinson et al. (1997a; 1997b) Woltemade (1997)
High Spring Discharge	Severe reduction in abundance and diversity of aquatic insects, with rapid subsequent recovery of all groups except Diptera.	DeBrey and Lockwood (1990)
High flow	Fish respond to even small increases in flow by moving upstream, but access to the river mouth is limited at high flows.	Schaffter (1997) Bergeron et al. (1998)
	Drifting goby larvae survive long enough to reach the sea only in above-normal flow conditions.	Moriyama et al. (1998)

Table 2 : Biotic Group Response to a Flow Regulated Stream (source Bragg et al 2005).

Group	Description	Literature Sources
Macrophytes	Absent from many regulated reaches, but nuisance growth occurs between remedial weirs.	Rorslett and Johansen (1996)
	Very high flows (in excess of 2ms□1) result in scouring of vegetation, substrate and fine organic material.	Gustard et al. (1987)
Invertebrates	Generally resilient to change within the UK range of compensation flow regimes, but family composition and abundance vary with flow regime.	Gustard et al. (1987)
	Impoverishment of invertebrate assemblages attributed to environmental changes, e.g., clogging of interstitial spaces in sediments resulting from regular flushing of upstream reservoirs.	Usseglio-Polatera and Bournaud (1989)
	Flushing and catastrophic drift of larvae resulting from intermittent 'hydropeaking' flows.	Plecopteran Cereghino and Lavandier (1998)
	Elimination of spring floods beneficial, but higher water temperatures and short-term summer flow fluctuations detrimental.	Casado et al. (1989)
Fish	Altered fish feeding habits due to effects of 'hydropeaking' on invertebrate	Lauters et al. (1996)
	High flows and sudden discharge fluctuations cause scouring, erosion and coarsening of spawning beds, and promote bank erosion with associated input of undesirable fine material.	Hendry and Cragg-Hine (1996) Kondolf et al. (1996)
	High current velocities exceed swimming ability, and thus restrict juveniles to areas of shallow water or thick weed.	Lightfoot and Jones (1996) Mann and Bass (1997) Flore and Keckeis (1998)
	Increased risk of juvenile strandings, especially if flow declines suddenly.	Debowski and Beall (1995) Bradford (1997) Armstrong et al. (1998)
	Disruption of cyprinid foraging by physical obstructions and alterations to the flow regime.	Lucas and Batley (1996)
	Water velocity and turbine operation influence salmonid movement at hydropower dams; although there is little firm evidence that freshet release aids salmon migration in the UK.	Gustard et al. (1987) Steig and Iverson (1998)
	Changes in reproductive development and spawning behaviour.	Auer (1996) McKinley et al. (1998)
	Changes in fish assemblages due to reduced availability and temporal persistence of key habitats, including floodplain isolation effects.	Nicolas and Pont (1997) Pinder (1997) Bowen et al. (1998)
	Only a small set of resistant species remain in bypassed reaches.	Klingeman et al. (1998)
General	Adverse effect on downstream communities, with reduction of macrophytes, fish and invertebrates.	Casado et al. (1989)
	Changes in sediment composition below dams, affecting benthic invertebrates and survival of fish embryos.	Petts (1988) Ibanez et al. (1996)
	Variations in flow velocity destroy pool/riffle relationships and create bank instability.	Gustard et al. (1987) Caffrey and Beglin (1996)
	Changes in sediment dynamics, with consequences for riparian forests.	Scott et al. (1996) Johnson (1997) Tremolieres et al. (1998)

2.3 Ecologically Relevant Metrics

The synthesis of flow parameters into one holistic methodology was first introduced by Richter et al (1996, 1997). This approach presented a set of 33 flow metrics based on their relevance to ecological quality, broken into five categories (as outlined by Poff et al., 1997): Magnitude, Duration, Timing, Frequency, and Rate of Change (Table 3). The synthesis of the 33 parameters was appropriately termed the Indicators of Hydrologic Alteration (IHA). The purpose of these 33 flow metrics is to characterize statistical properties of a flow regime over a long-term horizon, typically 20 years (Konrad and Booth 2002). Each metric has been proven to be associated with some influence on the ecosystem. Subsequently, the Range of Variability (RVA) approach was developed to set a range of natural variability about a measure of central tendency. This range is calculated for each IHA parameter and can be used as a measure of acceptable variability in the flow regime over time as it may change due to upstream developments.

Table 3 : Indicators of Hydrologic Alteration Parameter Grouping and Identification.

Group	IHA Parameter	Unit
GROUP 1 - MAGNITUDE	Average October flow	m^3/s
	Average November flow	m^3/s
	Average December flow	m^3/s
	Average January flow	m^3/s
	Average February flow	m^3/s
	Average March flow	m^3/s
	Average April flow	m^3/s
	Average May flow	m^3/s
	Average June flow	m^3/s
	Average July flow	m^3/s
	Average August flow	m^3/s
	Average September flow	m^3/s
GROUP 2 - MAGNITUDE AND DURATION	Average annual 1-day minimum flow	m^3/s
	Average annual 3-day minimum flow	m^3/s
	Average annual 7-day minimum flow	m^3/s
	Average annual 30-day minimum flow	m^3/s
	Average annual 90-day minimum flow	m^3/s
	Average annual 1-day maximum flow	m^3/s
	Average annual 3-day maximum flow	m^3/s
	Average annual 7-day maximum flow	m^3/s
	Average annual 30-day maximum flow	m^3/s
	Average annual 90-day maximum flow	m^3/s
	Number of days per year with zero flow	–
	7-day minimum flow divided by mean flow for that year	–
GROUP 3- TIMING	Julian date of the minimum flow	–
	Julian date of the maximum flow	–
GROUP 4- FREQUENCY	Average number of low pulses, low pulse defined as 1 standard deviation above the mean	–
	Average duration of low pulses	–
	Average number of low pulses, low pulse defined as 1 standard deviation below the mean	–
	Average duration of high pulses	–

Table 3 (continued).

GROUP 5-RATE OF CHANGE	Rise rate−mean of all positive differences	m^3/s/day
	Fall rate−mean of all negative differences	m^3/s/day
	Number of flow reversals	–

Olden and Poff (2003) noted that the large set of IHA parameters seemed intimidating and confusing to some researchers, and attempted to identify a sub-set of selected parameters that would characterize streams in a non-redundant manner through correlating IHA parameters and ecological characteristics for 420 diverse watersheds. A set of additional studies attempted to reduce the number of IHA parameters to a more usable and study-specific size. Scoggins (2000), Booth et al. (2004), and Kirby (2003) correlated IHA parameters with biological data to determine the most significant parameters. Clausen and Briggs (2000) also recommend utilizing a suite of different variables from the outlined groups ensuring that different components of the flow regime be adequately represented. In all cases, however, it is recommended that most if not all of the 33 indices be considered for watershed analysis. There is a risk of losing information when relative differences are averaged across indices within the groups (Suter 1983). Authors Karr 1991, 1993, Keddy et. al., 1993, and Minshall 1993 have all emphasized the importance of using a multi-parameter group of indices to assess ecosystem integrity, and they argue it is highly unlikely that any one parameter will have the sufficient sensitivity to be useful under all circumstances.

2.4 Application of Indicators of Hydrologic Alteration (IHA) Methodology

The IHA methodology was originally designed with intent to help scientists and policymakers examine changes in flow regimes caused by dams. As researchers are discovering, however, it can be applied to a large range of hydrologic and ecological studies. The hydrologic alteration is quantified by analyzing the medians and measures of variability between the predevelopment period and the post-development period using the Range of Variability Approach (RVA) (Richter et al, 1997). This method allows for the calculation of a percentage of change in the ecologically relevant streamflow statistics. The RVA is used to help prescribe restoration targets (Figure 1). The ecosystem flow restoration targets are numerical ranges within which the streamflow statistical variability should be maintained.

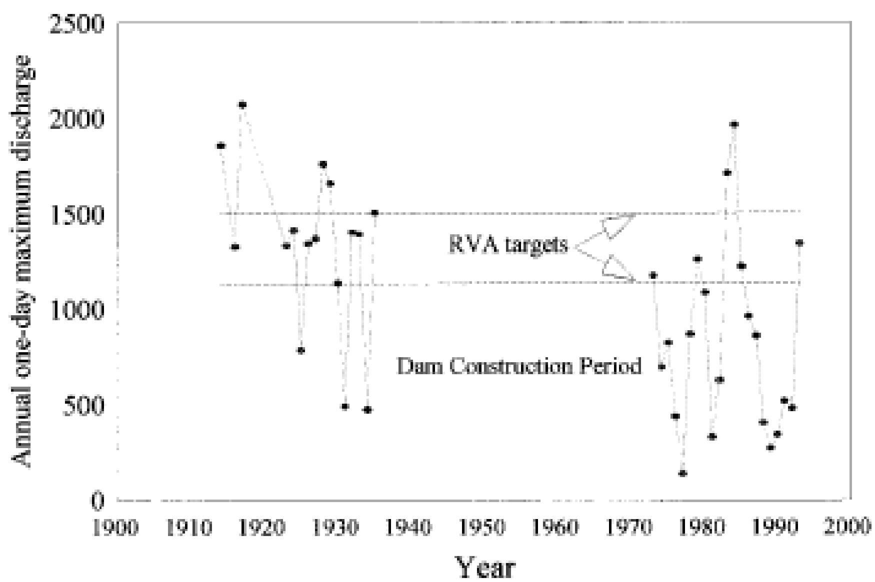
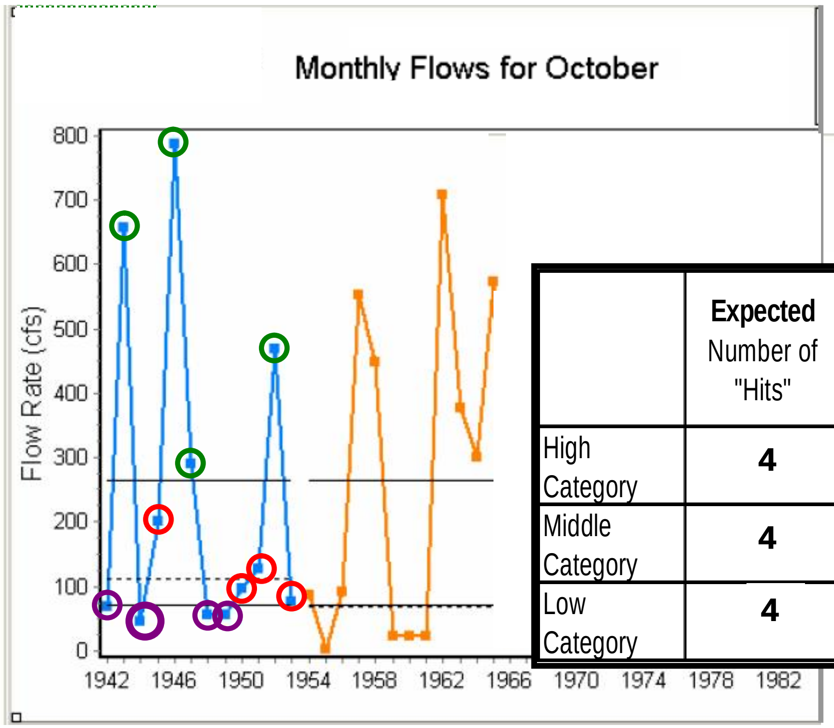


Figure 1: RVA Target Establishment and the Frequency of Data Points that Fall within the three Ranges. (Source Richter et. al 1998)

The goal for a sustainable river would be to maintain the same variability in median flow values when comparing pre-development with post-development. One approach to calculate change in variability based on the IHA is to count the median flow data points within three target ranges: low, medium, and high. When both the pre- and post-development datasets maintain the same frequency (number of data points) within the low, medium, and high range, the goal has been achieved. When the data points do not fall within the same range, it is considered an IHA “Mis-Hit.” Each of the 33 IHA parameters will have an associated Mis-Hit, ranging from zero to some maximum count which is dependent on the number of years modeled in the scenario. By summing these Mis-Hits over the 33 IHA indices the total count reflects a degree of ecological degradation. In this methodology, the sum of Mis-Hits is used as a metric for hydrologic alteration. Figure 2 shows an example of this process for obtaining the Mis-Hit count for the Monthly Flows for October parameter over a total of 12 predevelopment years (1941-1952) and 12 post-development years (1954-1965). The *expected* number of Hits refers to the pre-development record, where the *observed* number of Hits refers to the post-development record, and the discrepancy between them accounts for the Sum of the Mis-Hits. This example shows just one of the 33 parameters, and therefore the total count could be several hundred for a twenty year record comparison. This metric is termed the IHA Sum of Mis-Hit Count (IHA-SMHC).



	Expected Number of "Hits"	Obseved Number of "Hits"	Obseved Number of "Mis-Hits"
High Category	4	6	2
Middle Category	4	2	2
Low Category	4	4	0

TOTAL COUNT IHA-SMHC=4

Figure 2: Counting IHA Mis-Hits using Monthly flows for October

2.5 Stormwater Management Model (SWMM)

Watershed hydrologic models are important tools for addressing the increasing demands and problems related to water resources management and implementation. Models are used to estimate and evaluate the quantity and quality constituents of streamflow and urban runoff, impacts of reservoir operations, urban land development, and a range of other processes (Wurbs, 1998). The significance of using such a mathematical model is the ability to isolate the effects of specific aspects of urban development by holding all other watershed properties constant. This enables engineered decisions to be made efficiently, ensuring future watershed sustainability. One of the main components of this research's methodology employs EPA's Storm Water Management Model (SWMM) to simulate urban runoff of futuristic development scenarios (Huber et al., 1992).

SWMM was developed between 1969 and 1971, and was one of the first models to simulate urban runoff from both a quantity and quality standpoint. Written in Fortran, the model is composed of a series of algorithms for the various operating blocks. SWMM is essentially a surface water budget model, and the first of its kind able to represent urban runoff and combined sewer overflow issues with associated cost estimates for storage and/or treatment controls. SWMM has the capability to combine hydrographs at different locations into a single hydrograph time series, representing just one location: the watershed outflow point. Among the many complexities of SWMM, the major components are the precipitation, infiltration, and urban runoff techniques.

The fundamental input to SWMM is the precipitation dataset. Generally the data is obtained from on-site gages, but can also be synthetically generated in lieu of historical records. SWMM can have up to ten rain gages for consideration in the simulation process, and for continuous simulation, hourly, or 15-minute interval data at least one gage is required. The main output to SWMM is the urban runoff and is modeled as a single event or long-term (continuous) simulation.

2.6 Final Remarks

Hydrologic simulation and computerization of watershed modeling has allowed futuristic scenarios of development and human induced impacts to be evaluated. In this research, urban runoff is continuously simulated and reported in 15-minute intervals for a total of twenty years under various development scenarios. The flow data is then transformed into daily averages and analyzed using the IHA/RVA technique. The IHA parameters provide a set of quantitative metrics to represent the various characteristics of the natural flow regime, and the cyclic and seasonal flow patterns that define the dynamic environment that maintains ecosystem health and integrity. The combination of the SWMM simulation and the IHA statistical analysis is the key connection in enabling analysis of the mechanistic linkage between hydrological dynamics and ecosystem health.

CHAPTER 3: Simulation-Optimization Framework to Support Sustainable Watershed Development

3.1 Introduction

Human manipulation of water flows due to development has been a leading cause of ecological degradation. Using the IHA/RVA method to assess the hydrologic alteration associated with each long-term development pattern, a plan for watershed development can be identified to specify the spatial location and total of quantity of allowable imperviousness that will minimize the IHA parameter alteration. An overview of the design procedure to address this watershed management problem is outlined in Figure 3.

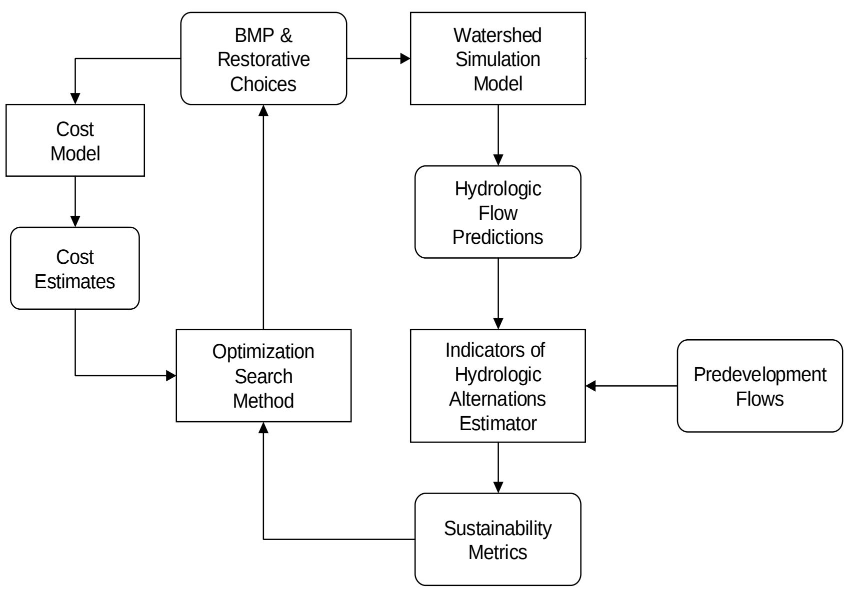


Figure 3 : Design Procedure for Simulation-Optimization Method

As Figure 3 outlines, this approach to sustainable development involves many different complex relationships between optimization, cost, watershed simulation, and hydrologic flow predictions.

3.2 Mathematical Model Formulation

The mechanism employed to address the causative link between increasing levels of imperviousness and ecosystem preservation is a mathematical optimization model. As outlined in Figure 3, BMP and restorative choices are iteratively updated and modified depending upon the IHA-SMHC results. However, design choices could also be user modified depending on the cost analysis.

The underlying goal of the optimization-simulation methodology is to find the optimal development pattern that has the least potential impact in altering the hydrologic flow regime.

The mathematical model for this problem is as follows;

$$Minimize\ \ Alteration = \sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} M_j^i \tag{3.1}$$

$$subject\ \ to \quad \sum_{n=1}^{SC} P_n A_n \geq T \quad and \quad P_n < U_n \quad \forall\ n \tag{3.2}$$

The penalty function is incorporated to aid the performance evaluation of the objective function and discount solutions that do not satisfy the one sided minimum development constraint. This can be represented as;

$$\textit{Minimize} \quad f = \sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} M_j^i + K \times \textit{Violation} \tag{3.3}$$

$$\textit{subject to} \quad \sum_{n=1}^{SC} P_n A_n \geq T \quad \textit{and} \quad P_n < U_n \quad \forall\ n \tag{3.4}$$

Penalty function to enforce development constraint;

$$\textit{Violation} = \begin{cases} T - \sum_{n=1}^{SC} P_n A_n & \textit{if} \left(T - \sum_{n=1}^{SC} P_n A_n \right) \geq 0 \\ 0 & \textit{otherwise} \end{cases} \tag{3.5}$$

Where M_j^i = number of Mis-Hits in each category *i* for each IHA Parameter *j*; *C* = number of categories for each IHA parameter (3 – High, Mid, Low); *IHA_P* = number of IHA parameters (33); P_n = percent imperviousness in subcatchment *n;* A_n = acreage of subcatchment *n*; *SC* = number of subcatchments in the watershed; *T* = total developed acreage in the watershed; and U_n = upper bound on the amount of development allowed in each subcatchment *n*. Specification of the upper bound deals with the assumption that for a given subcatchment 100% development is generally not attainable due to common construction practices and aesthetic nature of architectural design which almost always includes greenery around the perimeter of buildings, houses, and other structures.

The solution to this problem will identify the development pattern that minimizes the total hydrologic alteration (Eq (3.3)), subject to total level of development constraints (Eqs (3.4) and (3.5)). The expressions presented here can be modified and evaluated based on the user's specific model and criteria; however, the following subsections will employ these functions for the analysis of a specific case study.

3.3 Illustrative Application to a Watershed Development Pattern

3.3.1 Background Information

The Rouge River Watershed encompasses approximately 438 square miles in southeastern Michigan and contains 1.5 million residents. The watershed covers three counties; Wayne, Oakland, and Washtenaw, and contains 127 river miles. Figure 4 shows the Rouge River and its four major branches; Lower, Middle, Upper, and Main. This figure also shows the boundaries of the 11 major subwatersheds, which include the Upper 1, Upper2, Lower 1, Lower 2, Middle 1, Middle 2, Middle 3, Main 1, Main 2, Main 3, and Main 4. The Rouge River watershed outlet discharges into the Detroit River, which eventually drains into Lake Erie. The Rouge River watershed is 50% urbanized with less than 25% undeveloped land. For modeling purposes ten different land uses categorize the Rouge River watershed and are listed in detail in Table 4.

The Rouge River has been identified as one of the most polluted rivers in the Great lakes basin. There exists several sources of pollution for which modeling and sampling efforts for river restoration have been underway for several years. The main sources of pollution include combined sewer overflows (CSOs), stormwater runoff, illicit discharges, failing and leaking septic systems, stream bank erosion, and increased flow variability.

Table 4: Land Use Categories and Percentage of Total Drainage Area

Land Use Category	Percentage of Total Drainage Area				
	Upper Rouge (64 sq mi)	Middle Rouge (113 sq mi)	Lower Rouge (95 sq mi)	Main Rouge (194 sq mi)	Total (466 sq mi)
Forest/Rural Open	18.7 %	24.1 %	24.4 %	10.4 %	17.7 %
Urban Open	5.7 %	4.4 %	1.8 %	4.7 %	4.2 %
Agricultural	2.7 %	12.9 %	27.1 %	1.2 %	9.5 %
Low Density Residential	11.0 %	10.0 %	3.3 %	6.4 %	7.3 %
Medium Density	39.9 %	23.3 %	26.4 %	49.7 %	37.2 %
Residential	4.1 %	3.2 %	1.4 %	2.8 %	2.8 %
High Density Residential	10.7 %	7.9 %	5.3 %	12.5 %	9.6 %
Commercial	3.7 %	8.3 %	8.7 %	7.8 %	7.5 %
Industrial	2.2 %	1.9 %	1.2 %	2.4 %	2.0 %
Highways	1.4 %	3.9 %	0.5 %	2.1 %	2.1 %
Water/Wetlands					
TOTAL	100.0 %	100.0 %	100.0 %	100.0 %	100.0 %

The current Rouge River modeling effort can be described in three phases. The first phase consists of several small area models used to simulate flows, pollutant loads and concentration from specific wetlands, ponds, or other localized areas. The second modeling phase involves a sewer system model in addition to a pollutant loading model. Both of these models simulate pollutant generation by subarea and cover the entire watershed. The third phase simulates instream flows for the four main subwatersheds and uses pollutant loading inputs from phase two to characterize instream water quality.

The specific software packages involved in these phases include the TRTSTORM (Kluitenberg, et. al, 1994), which is a modified mass balance model of the Army Corps of Engineers Storage, treatment, overflow, runoff model (HEC, 1976). This model tracks the CSO systems. Additional modeling software used includes the Watershed Management Model (WMM), which generates annual pollutant loading estimates from the various sources. This model allows for certain BMP and CSO controls to be implemented to determine overall pollutant loading reduction for sustainability and management purposes. In addition EPA's SWMM model is used to model the hydrology of all natural drainage areas with storm sewers. A SWMM RUNOFF/TRANSPORT model was developed in 1994 and is used to model all the CSOs entering the river. By utilizing USGS streamflow gauges for continuous data, as well as inflow hydrographs from the CSO and RUNOFF models combine to then generate a one-dimensional river model referred to as the SWMM TRANSPORT model.

The Middle Rouge River, 70,000-acres in size, is one of the four main subwatersheds contributing to the Rouge River (Figure 4). Water quality improvements have been an ongoing effort of policymakers in the Detroit and suburban areas. Overflowing CSO's and highly polluted storm water runoff has left city planners scrambling for answers. EPA has been funding the Rouge River Wet Weather Demonstration program since the early eighties. In addition, multiple TMDL programs are underway.

The United States Geological Survey (USGS) has several streamflow gauges located on the Rouge River. These gauges report daily and continuous flow values, in additional to water parameters at certain locations. This data coupled with water quality trends can help assess significant alterations due to urbanization. Figure 5 shows the entire record (1950-to date) of daily average streamflow in the Middle Rouge River.

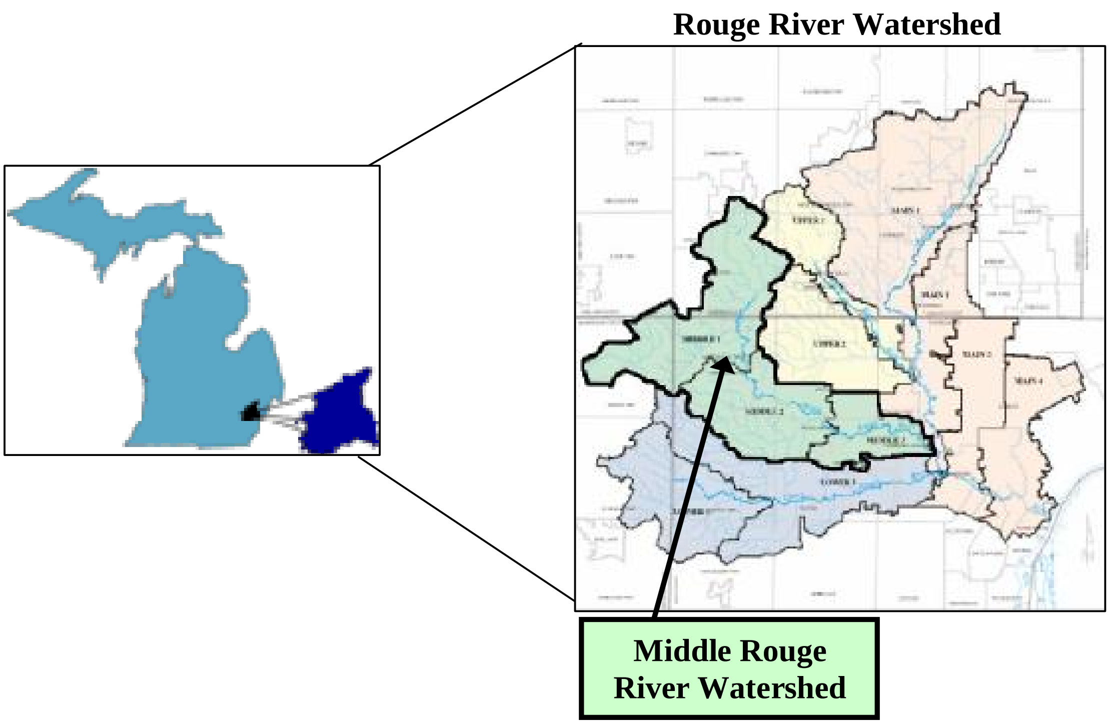


Figure 4: Rouge River Watershed Geographic Reference (Source: Wayne County DOE/RPO)

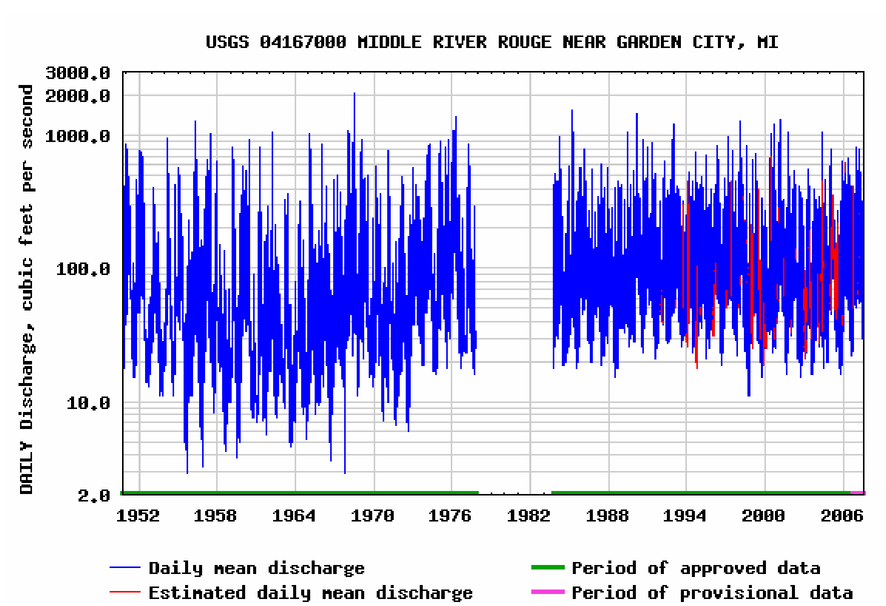


Figure 5: Gauged Streamflow Record for 50 years for the Middle Rouge River (Source: USGS)

There is a subtle transformation of the daily streamflow averages, streamflow variability, and median streamflow values from the 1960's to the 1990's, highlighting potential human-induced impact. The Baseline Data Summary report of 2000 also highlights water quality transitions in what might be considered as the post-development period. Rapid changes in dissolved oxygen and nutrients are reported, in addition to reported increases in eutrophication and aesthetic degradation (Baseline Data Summary, 2000).

3.3.2 Model Parameters

The Middle Rouge River watershed is modeled using SWMM, which for the particular area was developed and calibrated by local environmental consultants in 1994 (Camp Dresser & McKee, Inc., 1994). At the time of model development, the seven subcatchments had an average of 5.8% imperviousness. Due to the minimal, if any, amount of ecological and biological samples collected during these conditions, efforts to transition the Middle Rouge River to some unknown predevelopment flow regime is impossible. The Middle Rouge River is, however, the least developed out of the four main subwatersheds mentioned earlier, and thus a perfect candidate for resembling predevelopment conditions in this analysis.

The main SWMM hydrologic modeling components outlined in Section 2.5 include precipitation, infiltration, and urban runoff. The precipitation record included in the model is a 15-minute dataset obtained from six local rain gages. The watershed outlet flow values are reported in 15-minute intervals, and are then converted to daily flow averages outside of SWMM. The seven subcatchments defining the study area have associated areas, slopes, and initial imperviousness outlined in Table 5. The seven subcatchments and their associated areas reflect the extent of the acreage modeled in this research. The slope refers to the ground slope of each subcatchment, and the initial imperviousness reflects the pre-development modeled conditions.

Table 5: SWMM Parameter Inputs for Middle Rouge River Case Study

Subcatchment ID	Total Area (acres)	Slope (%)	Imperviousness (%)
1	757.12	0.00818	4.619
2	739.66	0.01064	5.884
3	1851.28	0.00972	5.444
4	2489.12	0.00714	9.733
5	2057.75	0.00636	3.849
6	2372.07	0.00414	4.509
7	1891.89	0.00874	6.599

3.3.3 Uniform Development Approach

The uniform development approach simulates urban runoff in the watershed without a mathematical optimization component for iterative development pattern decision making. Uniform development essentially reflects an unsustainable approach to watershed development because it sequentially increases the imperviousness in each subcatchment without considering the associated changes to the natural flow regime taking place. Sensitive areas in the watershed that become developed go unmitigated in this approach. The IHA/RVA technique described previously is used to model twenty-years of daily average streamflow values for a total of eight different uniform development scenarios. Each uniform post-development scenario is evaluated against the pre-development flow regime to obtain a corresponding IHA-SMHC for that record. The pre-development condition is represented with an IHA-SMHC equal to zero, and acts as the baseline. The uniform post-development scenarios include 10, 15, 20, 25, 30, 45, 60, and 100% imperviousness. Figure 6 shows the resulting IHA-SMHC versus total developed acreage for these eight scenarios, and the results are summarized in Table 6.

As the literature has revealed, the link between development induced manipulation of the flow regime and biotic change is strong, and therefore we are assuming that a higher IHA-SMHC correlates with increased ecosystem degradation. As Figure 6 highlights, the increase in IHA-SMHC is extremely responsive in the 6% to 45% post-development range showing an increase in Mis-Hits from zero to 355. Further increase from the 45% IHA-SMHC level to 100% only yields 27 additional Mis-Hits, a seemingly small IHA-SMHC increase for 55% additional imperviousness. This guides a notion that once a certain level of development has been reached without proper watershed management techniques, ecosystem damage has occurred, and development to 100% induces no further significant increase in the IHA-SMHC.

Table 6: Total Developed Acreage and IHA-SMHC for Uniform Development Scenarios

	DEVELOPED ACREAGE IN EACH SUBCATCHMENT								
Subcatchment ID	*Uniform 5.8%*	*Uniform 10%*	*Uniform 15%*	*Uniform 20%*	*Uniform 25%*	*Uniform 30%*	*Uniform 45%*	*Uniform 60%*	*Uniform 100%*
1	35	76	114	151	189	227	341	454	757
2	44	74	111	148	185	222	333	444	740
3	101	185	278	370	463	555	833	1111	1851
4	242	249	373	498	622	747	1120	1493	2489
5	79	206	309	412	514	617	926	1235	2058
6	107	237	356	474	593	712	1067	1423	2372
7	125	189	284	378	473	568	851	1135	1892
Total area	733	1216	1824	2432	3040	3648	5472	7295	12159
IHA-SMHC	0	204	278	307	320	339	355	362	382

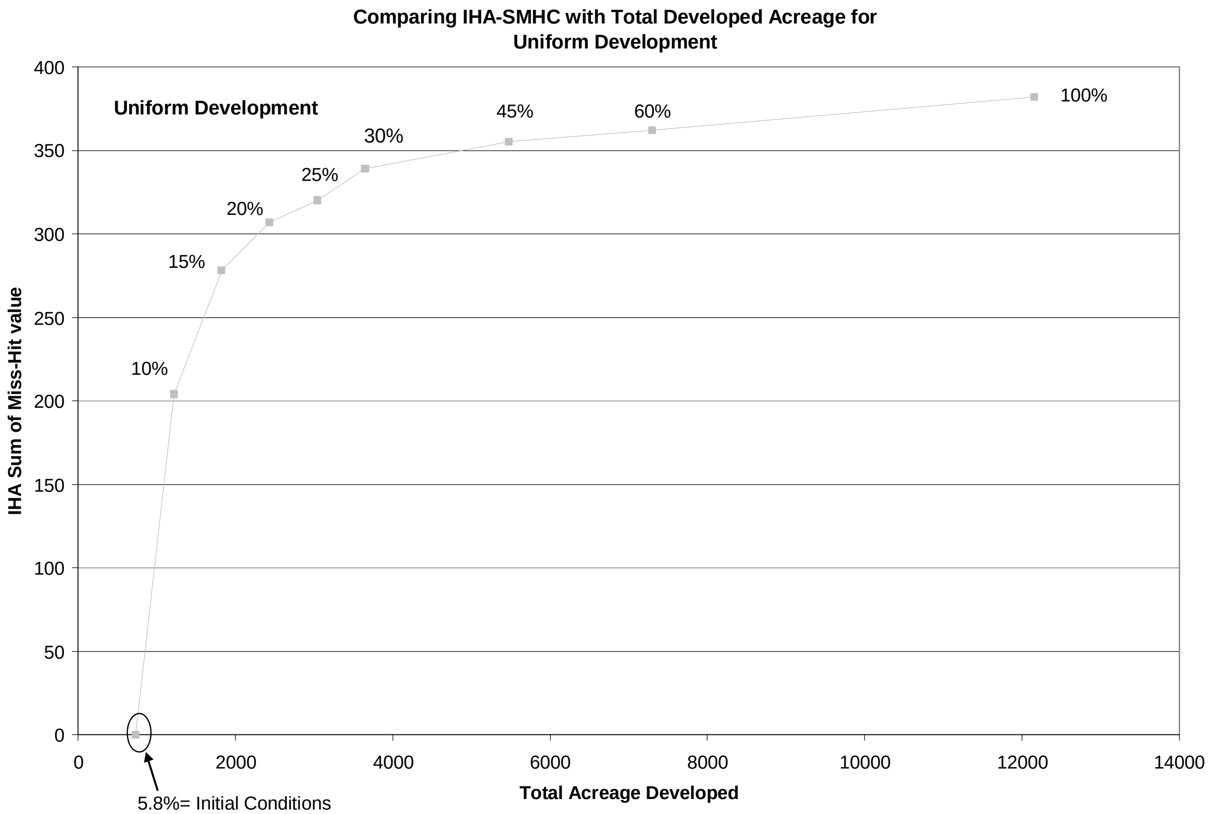


Figure 6: Uniform Development Approach Solutions for Eight Gradients of Development

3.3.4 Optimized Development Approach

Given the notion that some level of development must occur, this research aims to implement a mathematical model that iteratively manipulates the development pattern in a non-uniform manner that is based on the simultaneous minimization of the induced hydrologic alteration, or IHA-SMHC, of the associated development pattern.

3.3.4.1 Nelder Mead and Genetic Algorithm Search Techniques

The mathematical model represented by Eqs (3.3-3.5) can be solved using several optimization techniques. This research first investigates three approaches. The first, the Nelder Mead (NM) algorithm, evaluates solutions (Eq. (3.3)) at the vertices of a simplex, which is a generalization of a tetrahedral region of space to n dimensions, and by an iterative procedure, it shrinks the simplex until the optimal solution (development pattern) for minimizing hydrologic alteration is reached. Alternatively, a Genetic Algorithm (GA) technique can be used to solve the problem. Genetic Algorithm fundamentals are inspired by documented traits of evolutionary biology. For example, the algorithm searches and evaluates solutions by incorporating mutation, selection, and recombination techniques. The performance of each solution is evaluated using a fitness function and similar to the notion of Darwinism, the fittest solutions survive. One of the most powerful attributes of the GA is its ability to combine parts of solutions from different locations in the decision space creating a more global search. However, once the algorithm has converged on a small part of the decision space, the global search attributes no longer benefit. The main distinction between the GA and NM is the indirect method criteria referring to the difference in how the two search techniques explore the decision space. A common classification is show in Figure 7.

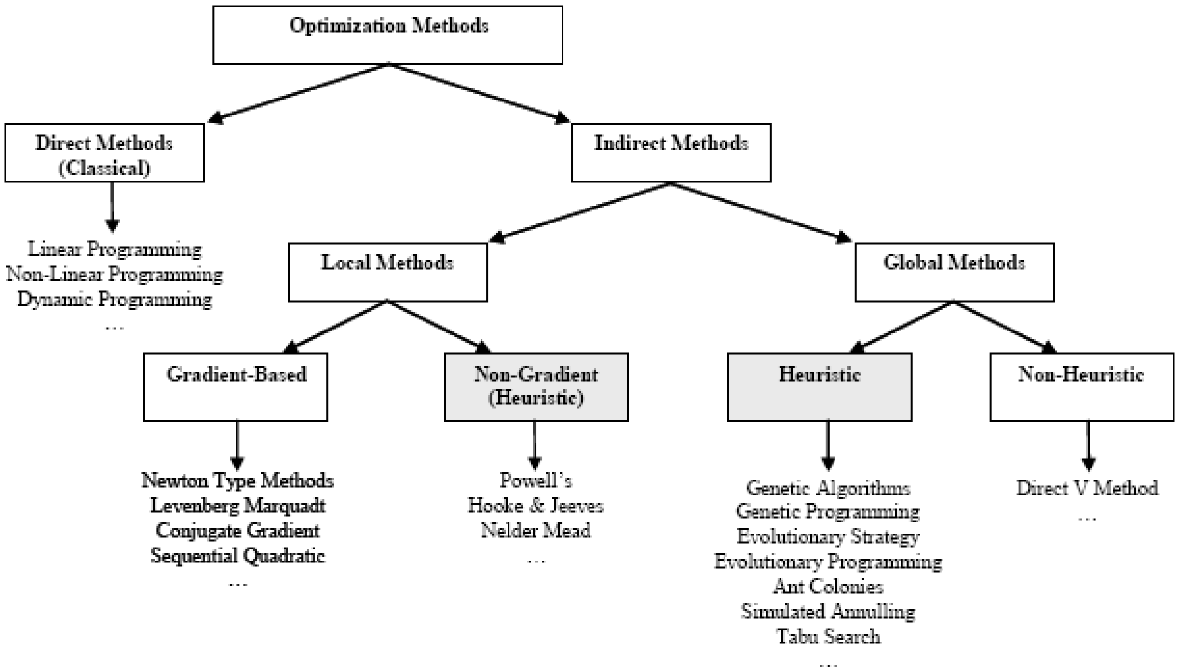


Figure 7: Common Classification of Optimization Techniques

3.3.4.2 Hybrid Algorithm Search Technique

The third approach investigated is a hybrid search technique. Hybrid methods for optimization are a common and efficient approach for solving complex optimization problems. Hybrid methods can be considered a combination of two or more search techniques into one methodology. This combination essentially formulates an optimization method with the best characteristics from the previous techniques. In this analysis, the Genetic Algorithm (GA) is used to quickly find a globally good solution, and then the Nelder Mead (NM) is used to fine tune that solution more locally. This hybrid approach is shown to be a more efficient method than each of the individual procedures for this application.

3.3.5 Results and Discussion

To explore the search methods, one level of development is selected, and ten random trials are executed for the NM and GA approaches as separate searches, with parameter settings outlined in Table 7, at the post-development level of 30%. These parameters are set at typical values, and could be explored in future analyses.

Table 7: Parameter Settings for GA Optimization Technique

Parameter	Value
Population Size	50
Probability of crossover (average % of strings that undergo crossover)	60%
Uniform crossover rate (average % of decision variables crossed over in a string)	28%
Mutation	uniform
Generation number at which the search stops, G^{max}	100

Figure 8 shows the results of the ten random seeds for both search techniques as they exist on the full range for uniform development scenarios. Figure 9 zooms in to view the 30% level for a closer examination of solution quality. The NM search results yielded a large variability in the solutions from both an objective fitness (IHA-SMHC) and decision space (developed acreage) perspective. The GA alternatively had solutions clustered more closely in objective space, and therefore could lead to reproducible results.

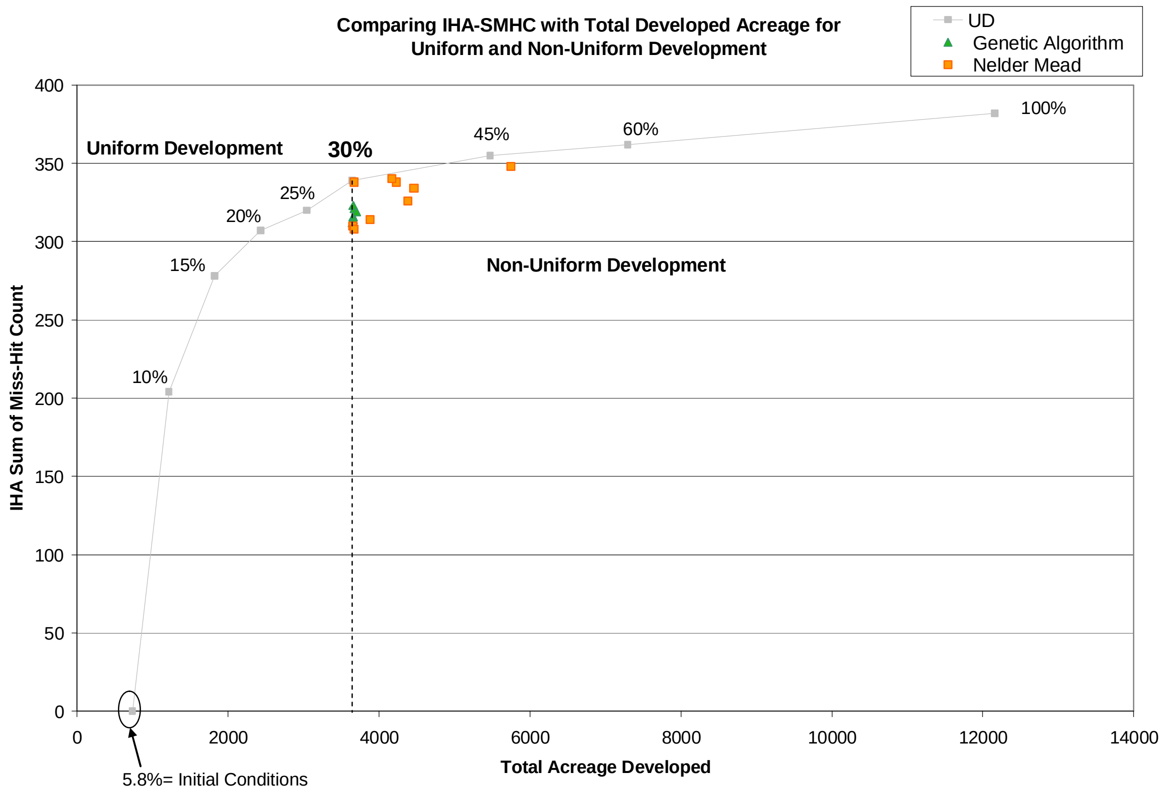


Figure 8: Optimization Development Approach Solutions for GA and NM Search Techniques at the 30% Development Constraint

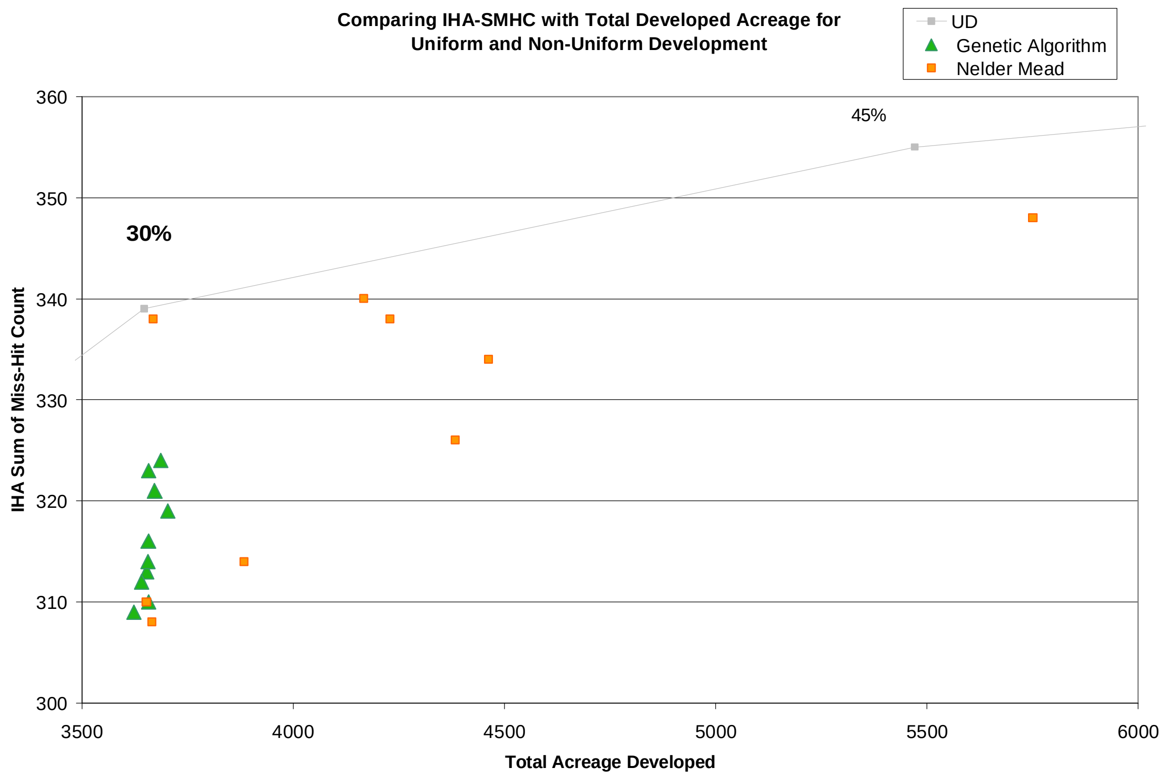


Figure 9: Examination of NM and GA Solutions at the 30% Development Constraint.

The typical and representative convergence behavior for two of the ten trails of the Genetic Algorithm is shown in Figures 10 and 11. These graphs reflect the variation of the best and mean objective function (IHA-SMHC) values obtained at each generation for the total simulation period of approximately 50 generations. The convergence behavior of the GA is an important aspect to the definition of the hybrid methodology used in this research. The GA exhibits variability in average function fitness from generations 1 through 15; after this point, the best fitness function and mean fitness function begin to coincide, reflecting that the GA has finished its global search. The point at which the GA has transitioned from a global to more local search is the point at which the NM is a better suited search. The hybrid approach is therefore the sequential combination of the GA to NM after the GA has completed 15 generations. The NM begins its local search with this seeded solution from the GA. From a computing time efficiency standpoint this hybrid approach is far superior. Further examination of when to stop the GA is warranted to potentially further reduce the computing time. This analysis would involve examination of the total population of solutions at each generation of the GA beginning with generation one. This further exploration will be addressed later in Section 5: Modeling to Generate Alternatives.

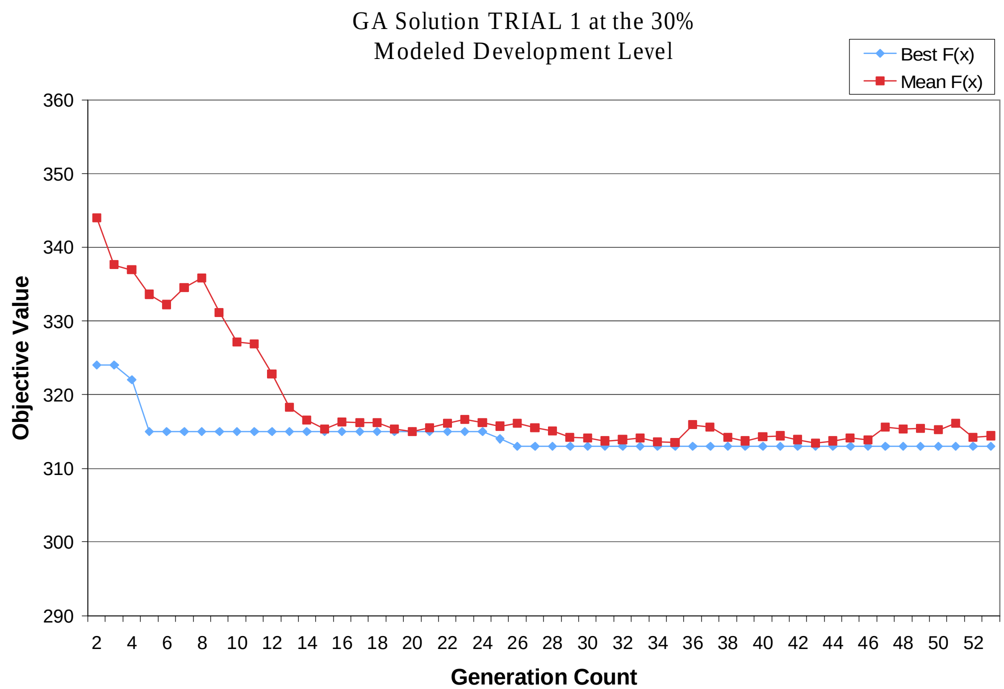


Figure 10: GA Solution Convergence for Trial 1 at 30% Modeled Development Level

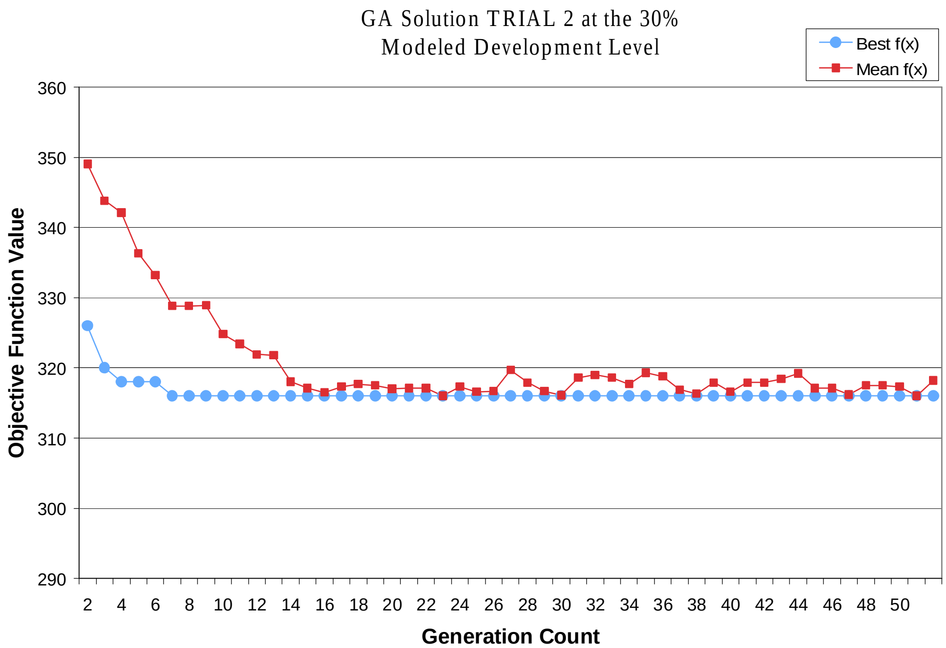


Figure 11: GA Solution Convergence for Trial 2 at 30% Modeled Development Level

The hybrid approach was applied to the entire development curve ranging from 10% (1,216 acres developed) to 45% (5,472 acres developed). This procedure was based on the results at the 30% post-development level using the two individual search techniques. For each of the six development levels explored, five random trials were executed and are presented in Figure 12. The optimized solutions are associated with less hydrologic alteration than the uniform development. One of the many benefits of the simulation-optimization framework is that it allows policymakers to allocate land for development with knowledge of the predicted hydrologic alterations associated with that scenario. Based on the watershed's ecosystem flow regime target (something that could change depending upon the site-specific initiatives), land development can be planned accordingly as to not exceed some predefined threshold. If the threshold is set at 300 IHA-SMHC, for example, uniform development would allow ~18% imperviousness, whereas the optimized scheme would allow nearly 30% imperviousness according to Figure 12. This increase in the amount of developable land made possible by the optimization method is a meaningful change and increased benefit from the standpoint of the watershed managers.

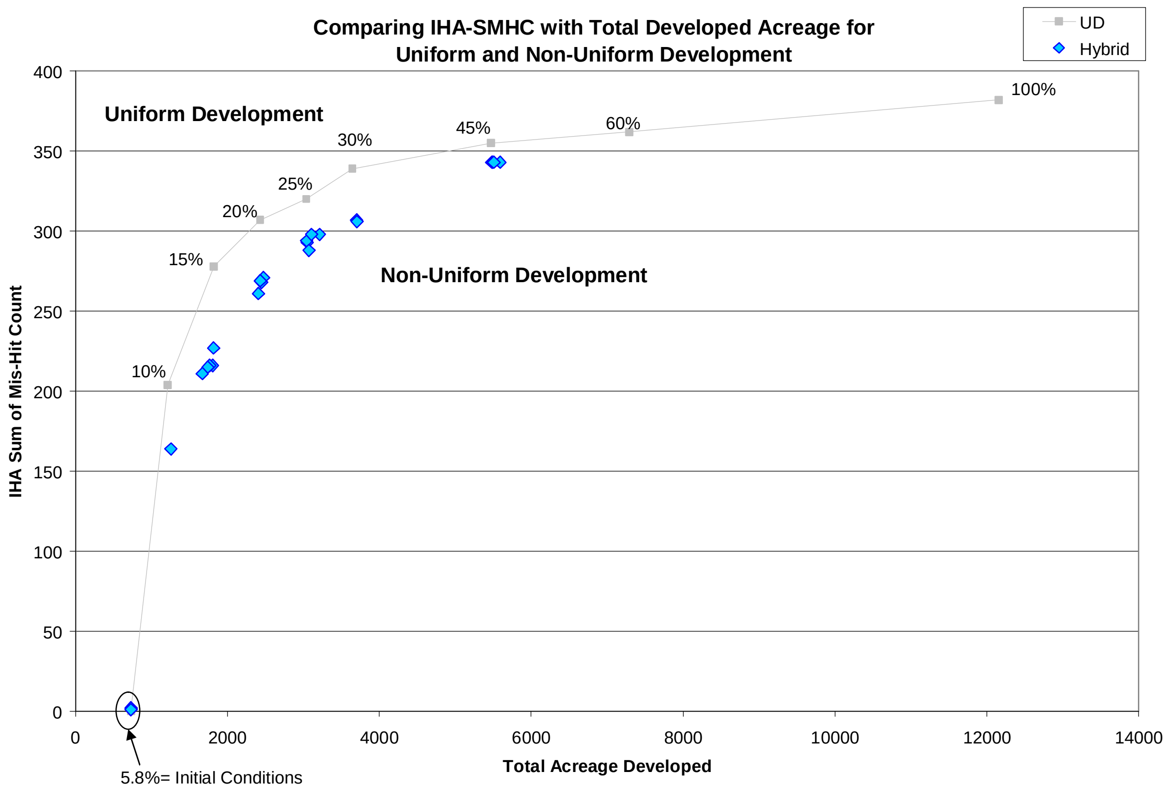


Figure 12: Non-Uniform Optimized IHA-SMHC versus Total Acreage Developed

3.4 Final Remarks

The hybrid simulation-optimization procedure approaches the problem with a quantitative modeling framework for mimicking the pre-development flow regime. This method is easily manipulated for any engineering problem of development design. The use of the Nelder Mead and Genetic Algorithm search techniques helped to define the characteristics of this illustrative case study application. The global search (GA) proved to be able to find a good solution more frequently, and the local search (NM) showed its ability to find the best overall solution, however with less consistency. The combination of these two techniques in the hybrid approach was used to map out the optimized non-uniform development curve for a large range of total development options. In addition, the IHA-SMHC showed flexibility in development allocation, proving that multiple development plans may exists for the same resulting degree of hydrologic alteration in the watershed.

CHAPTER 4: Comparative Analysis of Development Solutions

4.1 Introduction

When two solutions with the same resulting hydrologic alteration have very different spatial distributions of development, the decision for which development plan to proceed with may seem a daunting task. Therefore, comparative analysis of development solutions is an important step in the overall procedure of this methodology, and takes into account the main driving forces embedded in this approach, while also acknowledging unmodeled issues. Firstly, the role of the subcatchments in the development allocation tradeoff can help to differentiate between solutions. Secondly, the IHA-SMHC metric and its corresponding 33 parameters change as a function of development, and the valuable information they provide as they change can help guide policymakers to differentiate solutions. Unmodeled issues include watershed site-specifics, namely distinct topographical regions, or ecologically critical sections that must be set aside as non-developable. In addition, the ability to implement flexible development allocation from a political and legal standpoint may change current development strategies.

4.2 Watershed Development Allocation Tradeoff

Using the NM and GA search techniques, two solutions were found with an IHA-SMHC of 310. These solutions, however, have different development patterns for the corresponding seven subcatchments (Figure 13). The absolute difference in total developed acreage between the two solutions is 1,577 acres, a large amount considering the 30% uniform development acreage is 3,648 acres. This result suggests a non-unique mapping from decision space to objective space, specifically; different development patterns in the watershed can produce the same resultant hydrologic alteration. As Figure 13 shows, two solutions (310GA and 310NM) have distinct development distributions among the seven subcatchments, yet maintain the same hydrologic alteration (IHA-SMHC) of 310. Subcatchments two and six have the most similar development, with subcatchment seven yielding the largest difference between solutions at nearly 620 acres (Figure 13). From the standpoint of the IHA-SMHC, there is no difference between the two solutions. The choice between the two solutions must now be left to policymakers to simultaneously consider unmodeled issues.

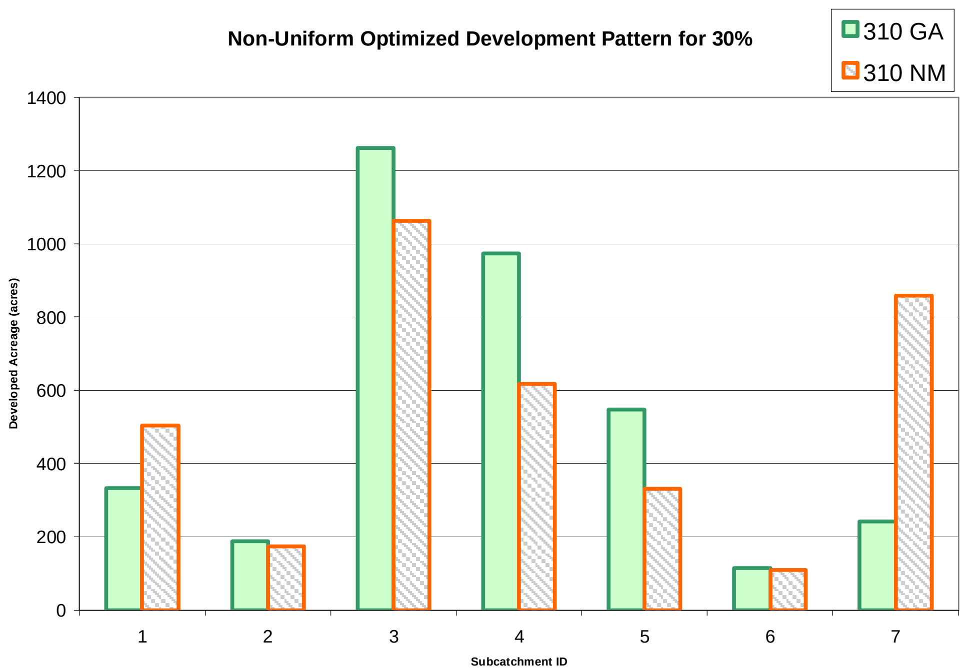


Figure 13: Comparison of GA and NM search solutions for IHA-SMHC = 310

Further analysis of the ten executed solutions and their corresponding difference in development was performed for the GA solutions whose total development amongst solutions remained more consistent than that of the NM solutions. Table 8 outlines the absolute differences in development for the ten GA solutions modeled at the 30% development level. This difference can be mathematically defined as:

$$\sum_{n=1}^{7} \left| P_{ni} A_{ni} - P_{nj} A_{nj} \right| \quad \text{for all pairs of solutions } (i,j) \tag{4.1}$$

Where P_n = percent developed land in subcatchment n, and A_n = acreage of subcatchment n.

Table 8: IHA-SMHC (for GA 30% solutions) versus the Absolute Total Change in Development between Solutions.

	310	312	313	314	316	319	321	323	324	309
310	-	3169	2361	2491	1791	2193	1044	2501	1566	2455
312		-	2934	2854	**4555**	1562	3372	2261	1976	1396
313			-	**271**	2495	2753	1837	2954	3086	2551
314				-	2335	2704	2001	2882	3037	2527
316					-	3325	2004	2626	2886	3648
319						-	2224	832	1263	1821
321							-	2056	1611	2401
323								-	1696	2431
324									-	3263

The smallest and largest differences in development are highlighted grey in Table 8 with values of 271 and 4,555 acres, respectively. The smallest difference in land development distribution corresponds to solutions 313 and 314, an IHA-SMHC difference of just one. The largest change in the distribution of development is found between solutions 312 and 316. The difference in the development distribution between these two solutions is

4,555 acres, and yet the difference in IHA-SMHC is four. One of the largest discrepancies in IHA-SMHC for the ten solutions evaluated is 14, and corresponds to solutions 324 and 310. The difference in development between these two solutions is 2,455 acres (Figure 14). In this example, although the development patterns appear similar, the IHA-SMHC alludes to a large discrepancy between them. Not only do these results show the complex tradeoff between IHA-SMHC and total development, but also the variety of feasible development pattern allocation plans for seemingly similar and different IHA-SMHC objectives.

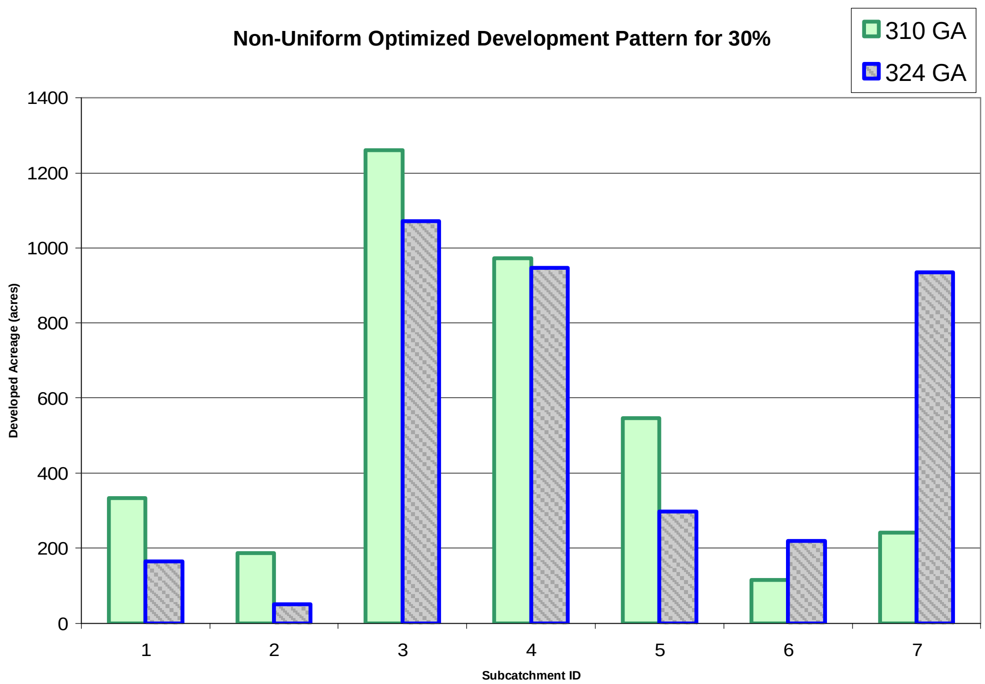


Figure 14: GA 310 and GA 324 Development Distribution and Allocation Comparison

Because of the increased computational efficiency with the hybrid approach, examination of six different development levels was performed. The six development levels are: 10, 15, 20, 25, 30, and 45%. The distribution of development within the watershed amongst the seven subcatchments proved to be unique even for solutions with the same IHA-SMHC. For the six development levels evaluated, only 45% had all five solutions with the same IHA-SMHC. At other development levels, all five executed solutions had both unique development allocations and IHA-SMHC values. Analysis and comparison of these results is included in Figures 15 through 20.

At the 10% level, the development allocation is somewhat uniformly spread with the exception of subcatchment four which accounts for the largest percent of total development. At 15% development, subcatchment seven accounts for the majority of development. The 20% level shows subcatchments five and seven reflecting nearly 50% of the total development. At the 25% level, subcatchments five and seven again reflect the largest portion of development. In the 30% and 45% solutions, there is a more uniform distribution of the majority of development among subcatchments three, four, and five, with subcatchment six accounting for the smallest percentage of total development.

As this analysis shows, certain development levels reflect an average tradeoff of development distribution with one or several subcatchments being more highly developed than others. Over the five executed solutions, however, this tradeoff shifts from one location to another causing development spikes to occur in different subcatchments with seemingly small IHA-SMHC tradeoff.

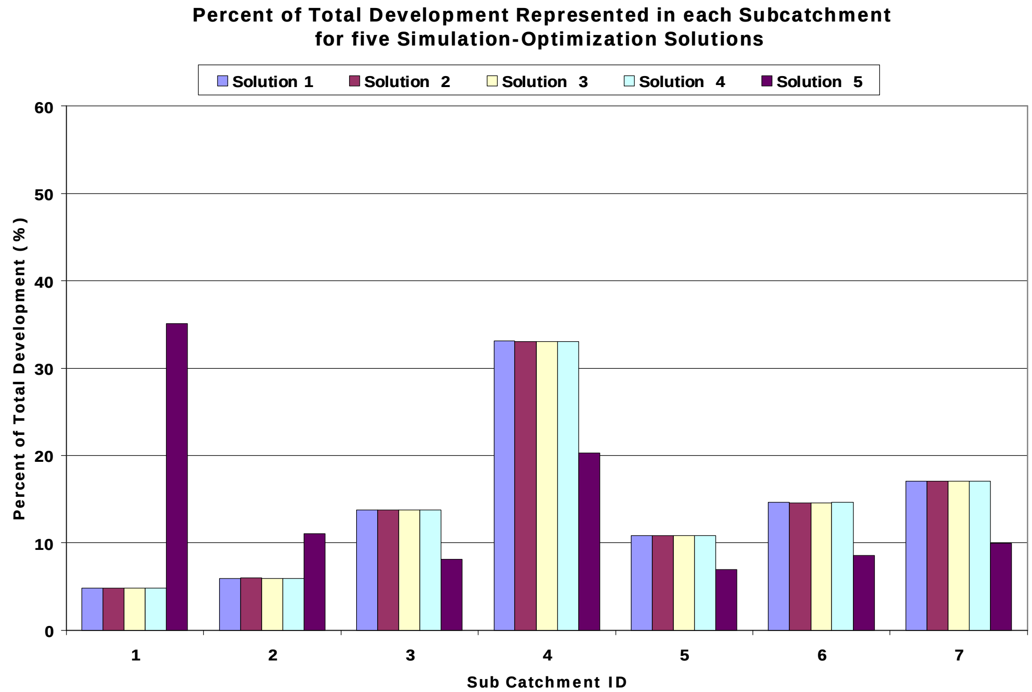


Figure 15: Distribution of Development for Solutions at the 10% Modeled Development Level

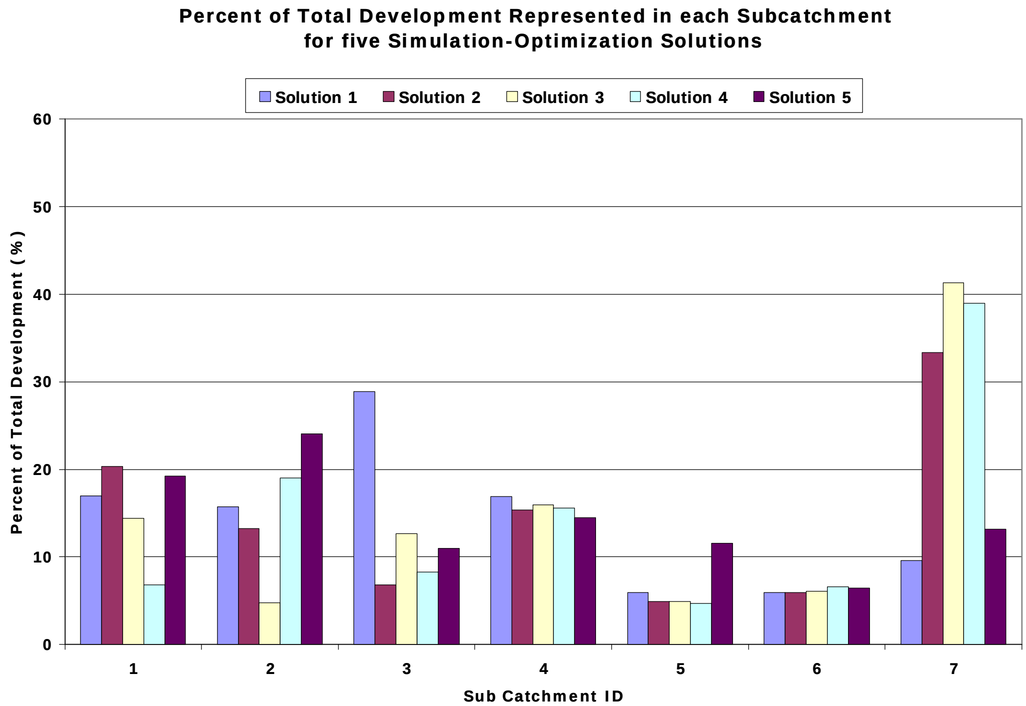


Figure 16: Distribution of Development for Solutions at the 15% Modeled Development Level

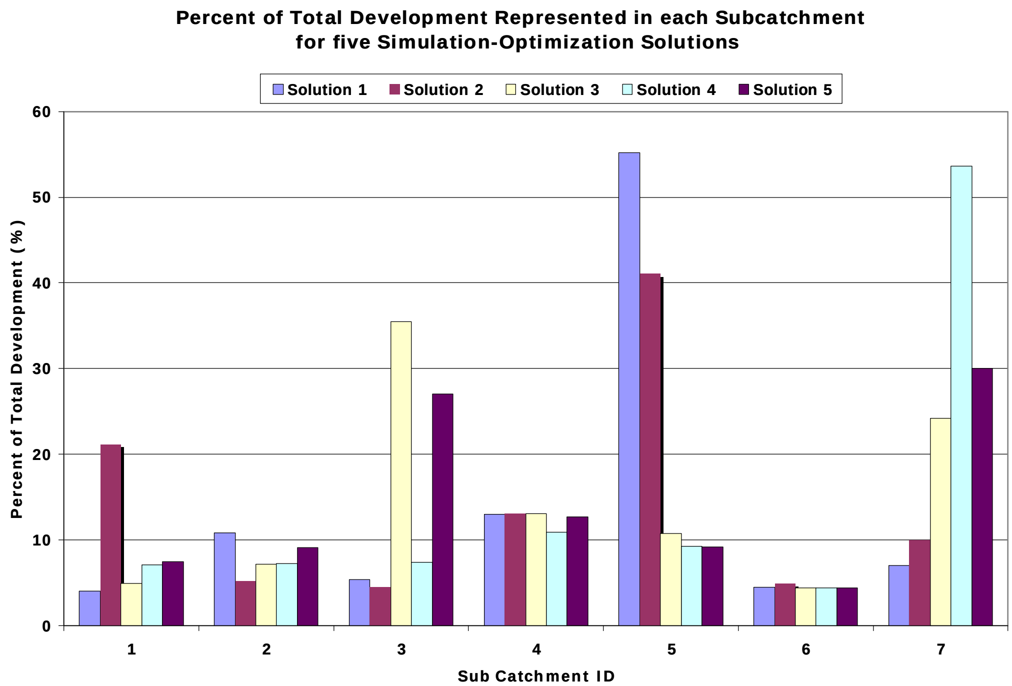


Figure 17: Distribution of Development for Solutions at the 20% Modeled Development Level

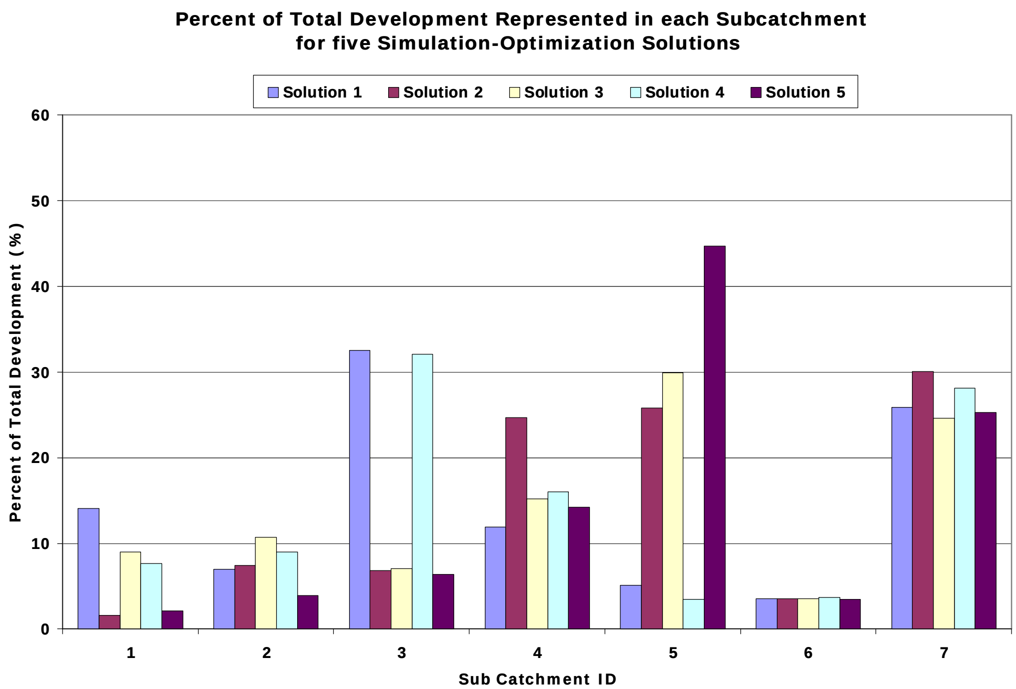


Figure 18: Distribution of Development for Solutions at the 25% Modeled Development Level.

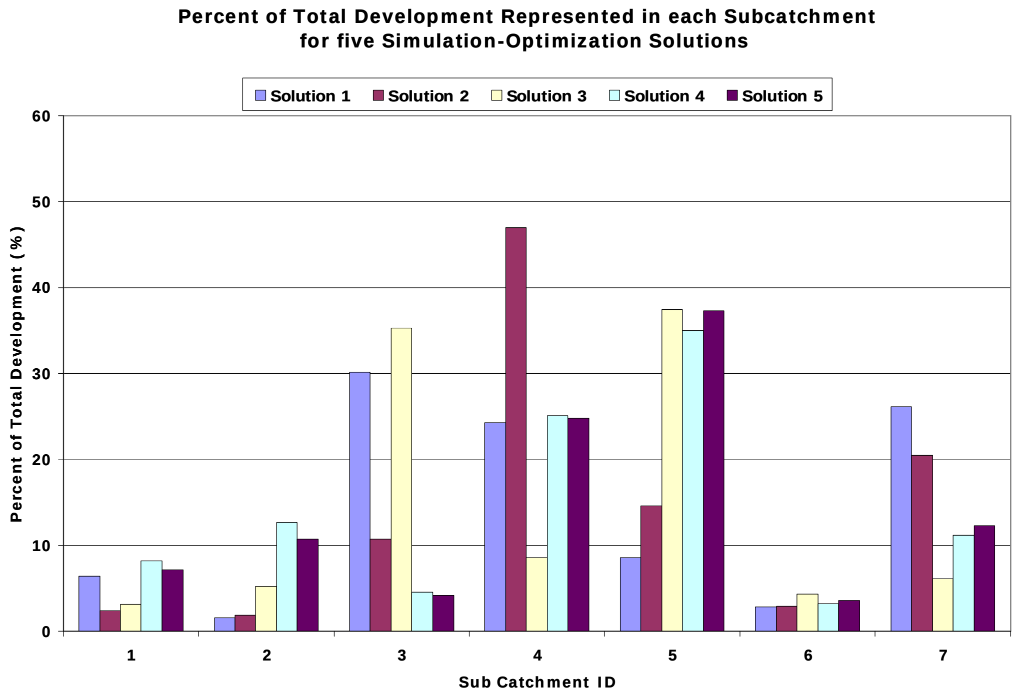


Figure 19: Distribution of Development for Solutions at the 30% Modeled Development Level.

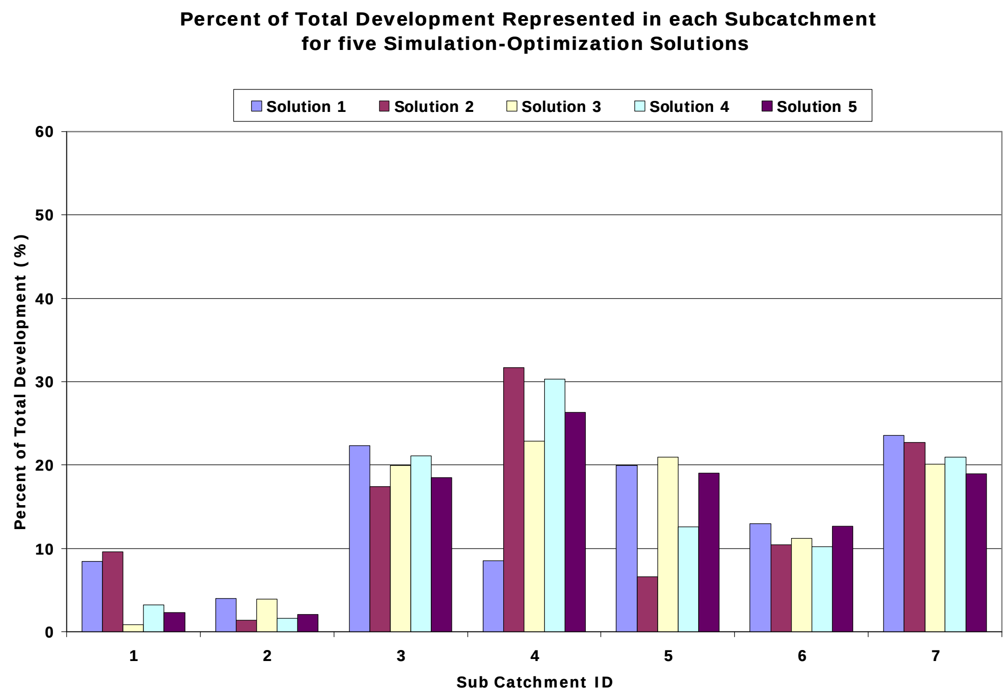


Figure 20: Distribution of Development for Solutions at the 45% Modeled Development Level.

In each of the modeled development levels the distribution of imperviousness in subcatchment six remains consistently one of the smallest. For the 45% development level subcatchments one and two account for less of the total development than subcatchment six. This high degree of variability in the distribution of development among the five executed solutions alludes to a fairly flexible allocation of development at all modeled percentages. To grasp the range of this flexibility, examination of just how different these solutions are needs to be analyzed. One way to represent this difference is to compare the percentage of total development differences across all seven subcatchments for any given two solutions. Mathematically, this can be represented as:

$$\sum_{n=1}^{7}\left|R_{ni} - R_{nj}\right| \qquad \text{for all pairs of solutions (i,j)} \qquad (4.2)$$

where: $R_{ni} = \dfrac{P_{ni}A_{ni}}{\sum_{n=1}^{7} P_{ni}A_{ni}}$

R_{ni} refers to the percent of total development that is reflected in subcatchment ***n*** for solution ***i***, P_{ni} refers to the percent developed land in subcatchment ***n*** for solution ***i***, and A_{ni} refers to the acreage of subcatchment ***n*** for solution ***i***.

Table 9 outlines the absolute differences between the executed solutions for all modeled development levels. This highlights how different the development distributions are from one solution to another normalizing for the difference in total acreage developed. The 10% level shows the smallest minimal difference amongst its solutions at 0%, meaning that at least two of the five executed solutions are identical for development in all seven subcatchments. The 30% level exhibits the highest maximal difference between solutions at 105%. Because this analysis is an absolute difference, the positive and negative differences between any two solutions are counted positively and therefore can result in a greater than 100% difference. The largest average difference for all five executed solutions occurs at the 20% modeled development level with a value of 75.1%. This suggests that the flexibility in development allocation is greatest at this modeled percentage level. Conversely, the 10% and 45% show the smallest average differences between solutions, and suggest that minimal amount of development alternatives exist at these levels.

Table 9: Absolute Percentage Differences in Development Distributions for all Modeled Development Levels

Modeled Development Level	Max Difference	Min Difference	Average Difference
10%	71%	0%	28.4%
15%	67%	27%	47.2%
20%	103%	21%	75.1%
25%	84%	30%	54.8%
30%	105%	7%	69%
45%	48%	13%	30.6%

In summary, this comparative analysis shows that the maximal flexibility in development alternatives exists in the elbow of the tradeoff curve around the 20% modeled development level. Less flexibility in development alternatives occurs at opposite ends of the elbow: the 10% and 45%. A difference in the IHA-SMHC for any two solutions can sometimes refer to a large difference in their development distributions, but as noted at the 45% development level this is not always the case.

4.3 Hydrologic Alteration Metrics

As previously introduced, the purpose of the 33 IHA flow metrics is to characterize statistical properties of the flow regime over a long-term horizon. Each metric has been proven to be associated with some influence on the ecosystem. The evaluator metric, IHA-SMHC, has been shown to increase with uniform development levels (Figure 6), but improve under optimized conditions (Figure 12). As Figure 6 also shows, the increase in IHA-SMHC is not linear with respect to the increase in development. If we consider each of the five solutions executed at the six modeled development levels, the overall change exhibited by the Mis-Hit counts is an important characteristic of each of the solutions. Results for the fraction of possible Mis-Hits fulfilled by each solution are summarized in Table 10. Figures 21 through 26 show the fraction of possible Mis-Hits within each IHA-Group for all solutions at the 10, 15, 20, 25, 30, and 45% development levels, respectively.

As development levels increase from 10% to 45% the fraction of total possible Mis-Hits in all five IHA-Groups increases. The IHA-SMHC metric reflects a more uniform representative amongst the five solutions than the development distribution showed. The count values represented in each group for a given percentage do not tend to vary for the five random solutions.

Table 10: Fraction of Possible Mis-Hits for each Executed Solution at all Modeled Development Levels Categorized by IHA-Group

	Solution	IHA-SMHC	Group 1	Group 2	Group 3	Group 4	Group 5
10%	Seed 1	1	0.00	0.00	3.57	0.00	0.00
	Seed 2	2	0.60	0.00	3.57	0.00	0.00
	Seed 3	2	0.60	0.00	3.57	0.00	0.00
	Seed 4	1	0.00	0.00	3.57	0.00	0.00
	Seed 5	164	33.93	35.71	7.14	37.50	57.14
15%	Seed 1	227	44.05	57.74	10.71	37.50	76.19
	Seed 2	216	44.05	52.98	10.71	33.93	73.81
	Seed 3	216	43.45	52.98	10.71	33.93	76.19
	Seed 4	215	42.26	52.98	10.71	35.71	76.19
	Seed 5	211	42.86	51.19	10.71	35.71	71.43
20%	Seed 1	268	56.55	65.48	17.86	37.50	88.10
	Seed 2	271	57.14	64.88	25.00	41.07	85.71
	Seed 3	269	57.14	65.48	17.86	37.50	88.10
	Seed 4	261	55.95	63.10	14.29	35.71	88.10
	Seed 5	269	57.14	65.48	14.29	37.50	90.48
25%	Seed 1	293	62.50	72.62	21.43	41.07	88.10
	Seed 2	294	63.69	71.43	21.43	42.86	88.10
	Seed 3	298	64.88	71.43	25.00	44.64	88.10
	Seed 4	298	63.10	73.21	21.43	46.43	88.10
	Seed 5	288	61.90	69.64	21.43	42.86	88.10
30%	Seed 1	307	68.45	72.62	21.43	48.21	88.10
	Seed 2	306	66.67	72.62	28.57	48.21	88.10
	Seed 3	316	67.26	77.38	25.00	51.79	88.10
	Seed 4	313	69.05	73.81	25.00	51.79	88.10
	Seed 5	314	69.64	73.81	21.43	53.57	88.10
45%	Seed 1	343	76.79	77.98	42.86	62.50	85.71
	Seed 2	343	76.19	77.38	42.86	62.50	90.48
	Seed 3	343	76.79	77.38	39.29	62.50	90.48
	Seed 4	343	76.79	77.38	39.29	62.50	90.48
	Seed 5	343	76.79	77.38	39.29	62.50	90.48

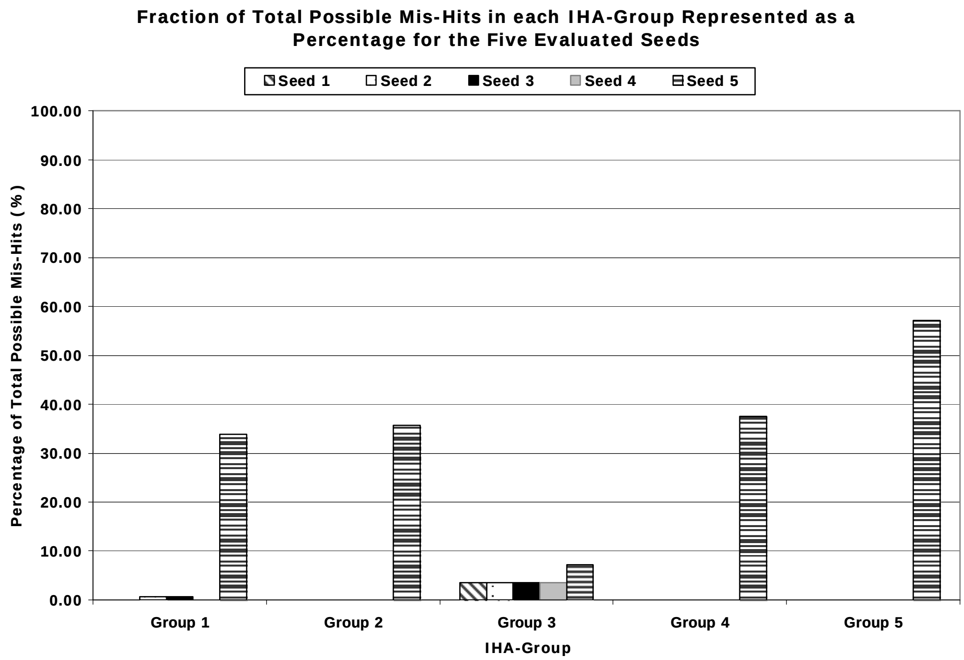


Figure 21: Fraction of Total Possible Mis-Hits for 10% Development Level Solutions

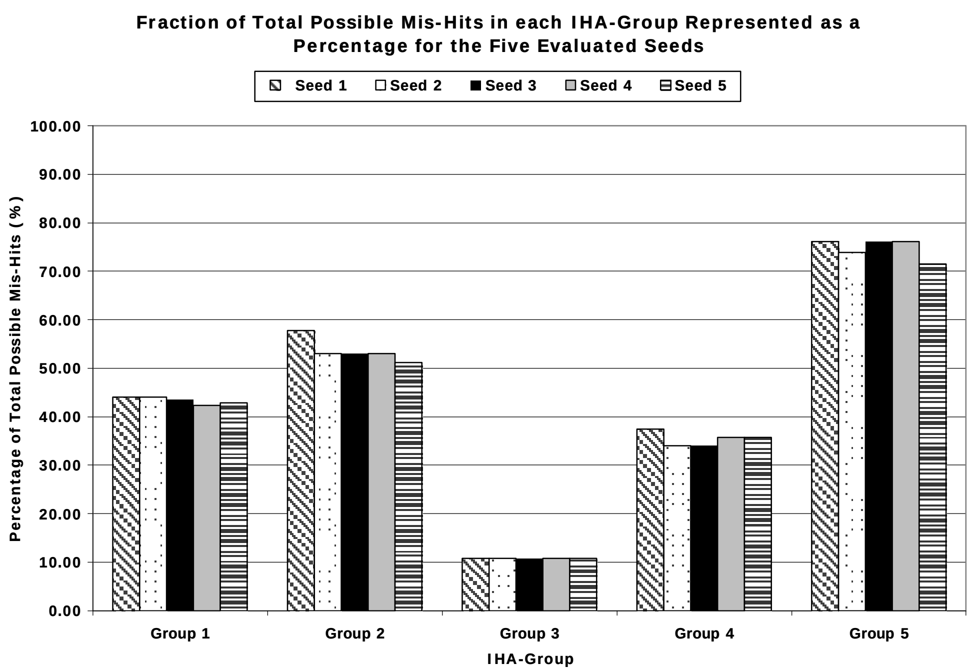


Figure 22: Fraction of Total Possible Mis-Hits for 15% Development Level Solutions

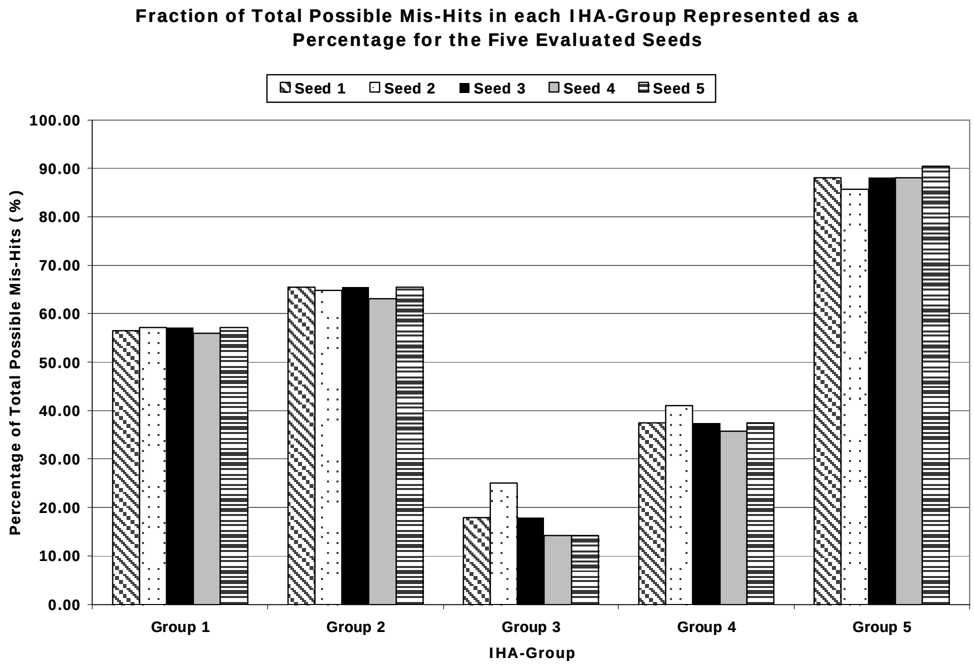


Figure 23: Fraction of Total Possible Mis-Hits for 20% Development Level Solutions

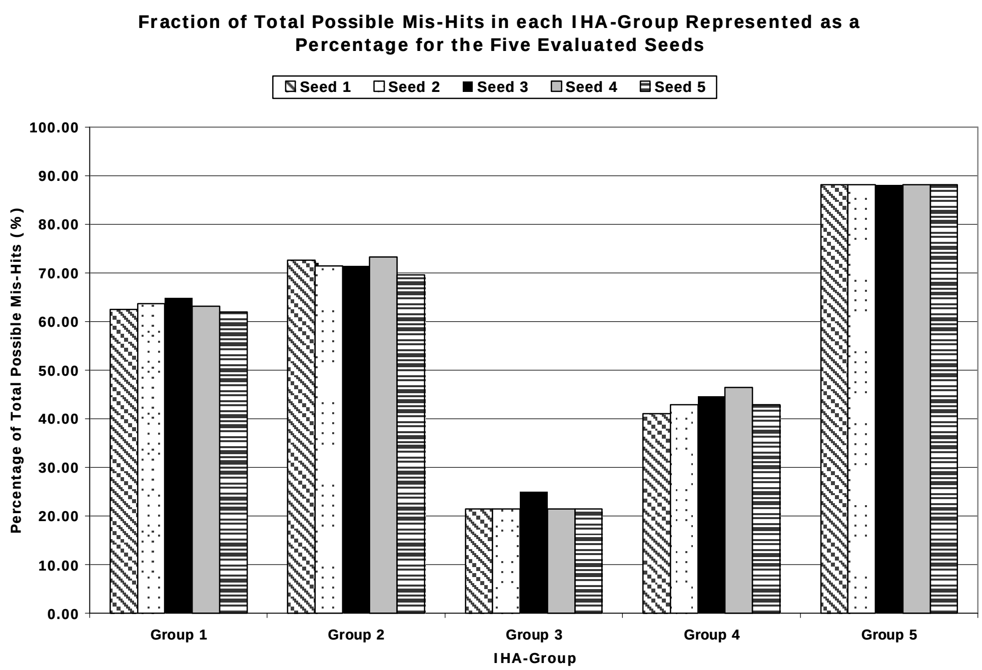


Figure 24: Fraction of Total Possible Mis-Hits for 25% Development Level Solutions

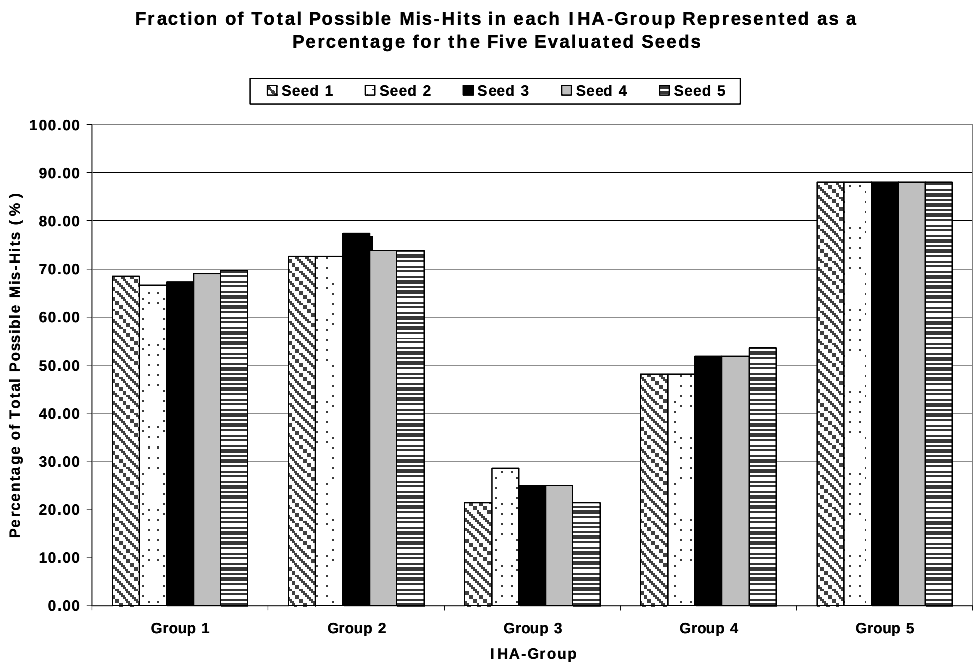


Figure 25: Fraction of Total Possible Mis-Hits for 30% Development Level Solutions

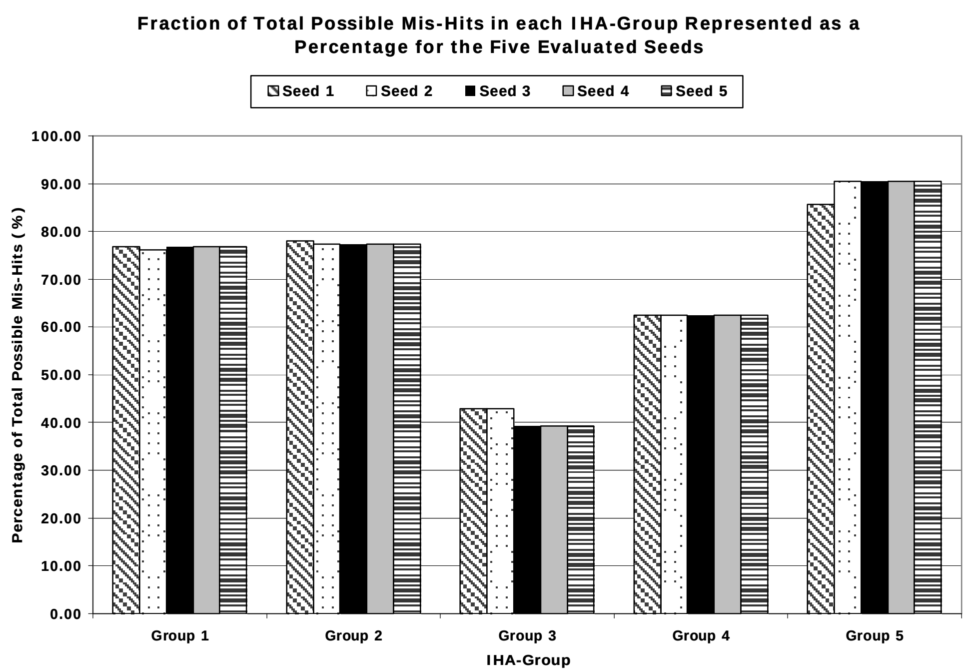


Figure 26: Fraction of Total Possible Mis-Hits for 45% Development Level Solutions

Figure 27 combines all the development levels and shows the average value of the fraction of total possible Mis-Hits within each IHA-Group. The IHA-Group that shows the highest fraction of total possible Mis-Hits at each development level is IHA-Group five. This IHA-Group reflects the rate of change indices, which measures the number and mean rate of positive and negative changes in water conditions over consecutive days (Richter et. al., 1997). Knowledge that this group of indices appears most responsive to changes in the development can help guide BMP retrofitting decisions to further decrease the hydrologic alteration. Each IHA-Group exhibits an increasing trend over the modeled development levels, and this methodology can help establish a priority ranking for BMP implementation according to those indices most responsible for the hydrologic alteration.

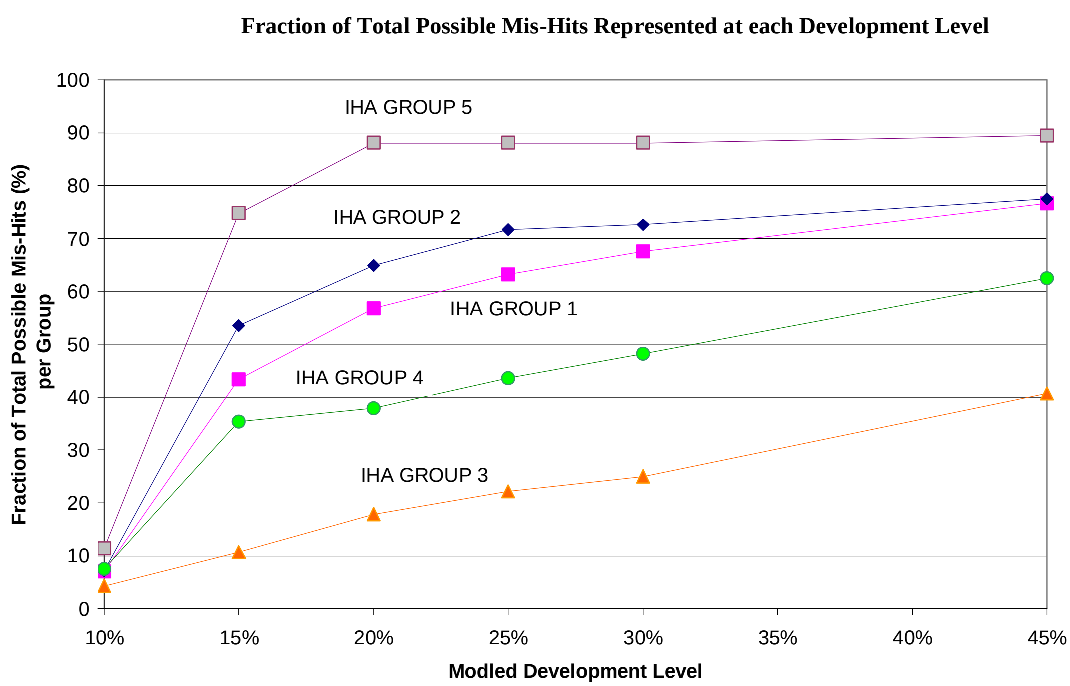


Figure 27: Fraction of Total possible Mis-Hits at each Modeled Development Level

4.4 Final Remarks

A large variety of solutions and alternatives are feasible for watershed managers to choose from for watershed development depending upon their target development level, ecological threshold, and interpretation of unmodeled issues. As was observed from these results, increasing the development in the watershed in a uniform manner will cause a certain level of hydrologic alteration. Improvement from this uniform level can be accomplished using the simulation-optimization approach. Optimized results yield a variety of development allocation plans, acknowledging that final decisions for development must incorporate specified unmodeled issues.

Interpretation of a watershed's ecological threshold involves evaluating the upper limit of hydrologic alteration acceptable as the watershed undergoes development. Different watershed will have distinctly different ecological thresholds depending on the designated use of the Riverine system, the native species, and water usage needs for human resources. This research points out several of the IHA parameters that appear most sensitive to change in the hydrologic flow regime.

These results help highlight the mechanistic linkage between hydrologic alteration and development. There are no solutions that suggest that an increase development can occur without the associated influence on the hydrologic deviation metric. The tradeoff is clear: a step towards more development is a simultaneous step towards a greater IHA-SMHC. This methodology has highlighted site-specific ecologically-relevant metrics that respond similarly and can be used to assess proper BMP retrofitting projects. Watershed manager should take into account the spatial distributions of all development plans in conjunction with unmodeled issues prior to making final decisions for development.

CHAPTER 5: Modeling to Generate Alternatives

5.1 Introduction

The degree to which the decision space can be different and still correspond to similar hydrologic alteration can be examined. From a watershed management standpoint, it would be ideal to quantify the degree of flexibility in the development pattern that would still ensure sustainability, or in this case, a maximally different solution with a minimal difference in IHA-SMHC compared to a good solution. Many limitations can be realistically addressed when it comes to decisions about how much and where development should occur. There are political and legal issues to consider. Therefore, having a plan for watershed development that allows flexible allocation can only improve chances for watershed management success.

This motivation is the reason for implementing a Modeling to Generate Alternatives (MGA) technique. MGA has been classified as a quantitative approach to search for solutions that are maximally different from each other, in addition to satisfying modeled constraints and objectives (Brill, 1979). The mathematical model for this problem will maintain the same constraints expressed earlier in Eqs (3.4) and (3.5), but will add the IHA-SMHC as a constraint instead of the objective (Eq(5.2)). The objective will then become:

$$Maximize\ f = \sum_{n=1}^{7} \left| (X_n - \hat{X}_n) \right| * A_n \qquad (5.1)$$

$$subject \quad to$$

$$\sum_{n=1}^{SC} P_n A_n \geq T \quad and \quad P_n < U_n \quad \forall\ n \qquad (see\ Eq\ 3.4)$$

Penalty function to enforce development constraint *Eq (3.5)*;

$$Violation = \begin{cases} T - \sum_{n=1}^{SC} P_n A_n & if \left(T - \sum_{n=1}^{SC} P_n A_n \right) \geq 0 \\ 0 & otherwise \end{cases}$$

Penalty function to enforce IHA-SMHC target;

$$Violation = \begin{cases} \sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} M_j^i - \sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} \hat{M}_j^i & if \left(\sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} M_j^i - \sum_{j=1}^{IHA\_P} \sum_{i=1}^{C} \hat{M}_j^i \right) \geq 0 \\ 0 & otherwise \end{cases} \qquad (5.2)$$

Where $\hat{X}_n$ is the decision variable value corresponding to the solution for which the IHA-SMHC constraint is set; M_j^i = alternative solution's number of Mis-Hits in each category *i* for each IHA Parameter *j*; $\hat{M}_j^i$ = known solution's number of Mis-Hits in each category *i* for each IHA Parameter *j*. *C* = number of categories for each IHA parameter (3 – High, Mid, Low); *IHA_P* = number of IHA parameters (33); P_n = percent imperviousness in subcatchment *n; A_n* = acreage of subcatchment *n*; *SC* = number of subcatchments in the watershed; *T* = total developed acreage in the watershed; and U_n = upper bound on the amount of development allowed in each subcatchment *n*.

Analysis of results will help define a degree of flexibility by quantifying the maximum difference between decision variables that can still yield a similar IHA-SMHC. Due to computing time, and the performance of previous approaches, a hybrid technique was used. This enables the GA is to complete approximately 15 generations before seeding the

NM search from that ending point for a more localized and shorter overall convergence. Parameter settings are kept the same, acknowledging that future studies could explore the associated influence of these values.

5.2 Results and Discussion

Based on the ten solutions obtained from the GA search at the 30% development level, the GA solution chosen to represent $\hat{X}_n$ for this analysis is the GA IHA-SMHC 310 solution. Using the mathematical model expressed above, an alternative solution that is maximally different from the GA solution can be obtained. The development constraint is originally set at 3,648 acres. In this analysis, the constraint is relaxed by 5% equating to an development constraint of 3,830 acres, in addition the IHA-SMHC target is set as a constraint at 325. This relaxation increases the algorithm's degree of flexibility in the search space. The $\hat{X}_n$ and X_n values for the GA and the MGA alternative solution are presented in Figure 28.

As Figure 28 highlights, the MGA alternative solution shows a large degree of difference in the development of the subcatchments. Although the MGA solution has a larger IHA-SMHC of 325 versus 310, the absolute difference in total development between the solutions is 6,379 acres (Eg 4.1). Figure 28 shows this comparison of imperviousness in each subcatchment between the two solutions and highlights their maximally different development pattern. When the GA solution has a highly developed subcatchment (three and four), the MGA alternative chooses to minimally develop that subcatchment.

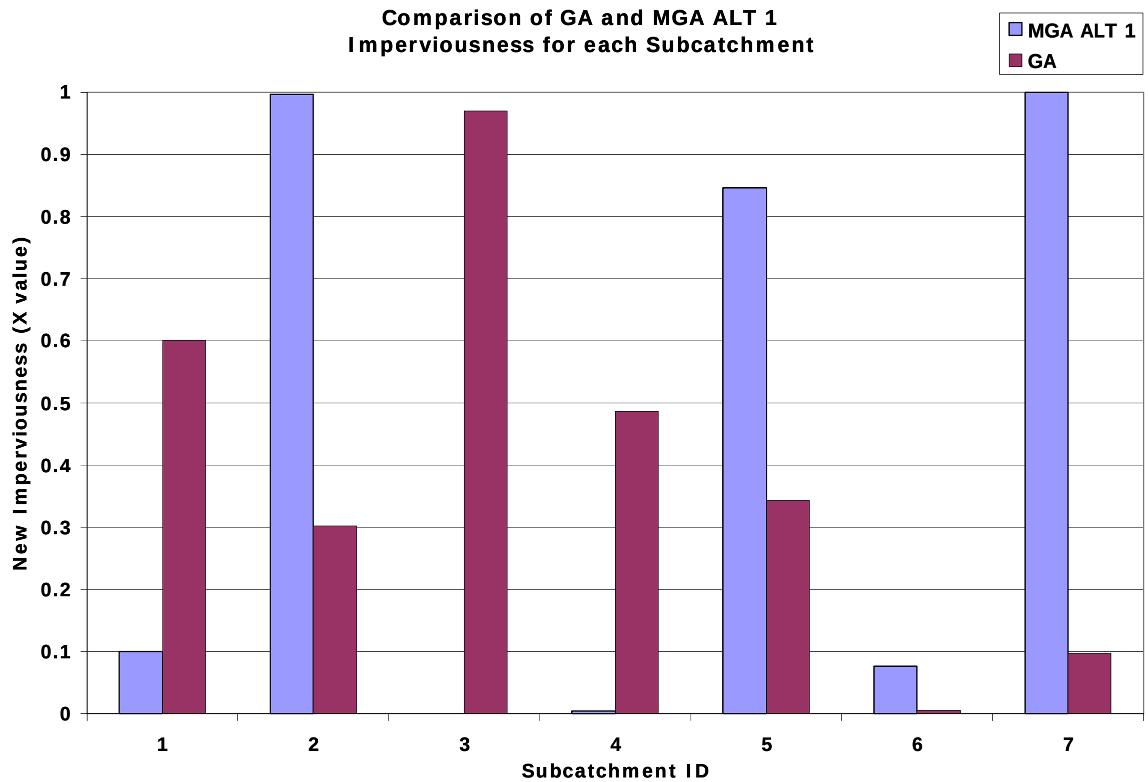


Figure 28: Comparison of GA (IHA-SMHC=310) and MGA (IHA-SMHC=325) Alternative Solutions for Development in each Subcatchment

5.3 Final Remarks

This MGA analysis helps highlight the large degree of flexibility that exists within the watershed development problem. This methodology of modeling to generate maximally different alternatives can aid decision makers in watershed development and management implementation. Using this information, decision makers can establish allowable bounds of minimal and maximal subcatchment imperviousness such that an acceptable level of hydrologic alteration is maintained. Certain subcatchments appear more sensitive to changes in the hydrologic flow regime than others. Some subcatchments yielded a difference in development between solutions of nearly 100%, suggesting they are able to be manipulated without causing a high degree of hydrologic alteration. This analysis helps establish the framework for watershed managers to understand and predict implications of development patterns. This methodology can provide the necessary quantitative bounds for subcatchment imperviousness that minimizes resulting hydrologic alteration, and allow decision makers to allocate development efficiently and effectively ensuring ecosystem health.

CHAPTER 6: Summary and Conclusions

Some aspects of the flow regime prove more vital than others to certain organisms. However, maintaining the pre-development variability in all flow regime parameters is a key step towards successful sustainability practices. Development strategies and allocation tradeoffs presented in this research expose the flexibility in achieving varying levels of development while meeting ecological criteria and thresholds. Establishing site-specific ecological alteration thresholds allows policymakers to determine which development scenarios to consider while meeting that target. Similarly, policymakers can observe the ecological alteration associated with various development alternatives to help determine the appropriate development plan. The use of hydrologic simulation models is an essential tool for understanding human influences on river flows and in the design of watershed management plans. As shown in this methodology, the hydrologic simulation model enables forecasting and prediction of the implications of each development scheme.

The IHA parameters provide a set of metrics to use as a convenient and practical approach for evaluating the degree of alteration from the pre-development conditions. The IHA-SMHC metric can be applied to all types of watersheds to evaluate different development plans. The metric can also be used in a simulation-optimization framework to iteratively evaluate development plans until an acceptable level of hydrologic alteration has been achieved. Many aspects of this problem allow watershed managers to become active members in the decision-making process. The non-uniqueness in solution space for development plans with similar or even identical objective function values provides several alternatives for decision makers. The hybrid optimization approach utilizes two different search techniques to improve computational efficiency and processing time for generating development plan solutions. This allows for more comparison among alternative designs resulting in the best possible decision for watershed development.

Human modification to the natural variability of the flow regime has irreversible consequences. Watershed development is a delicate and complex process. There necessarily needs to be multiple evaluations of all contributing variables. Without such analyses, the end result will be increased alteration of the ecosystem. If ever there was a point in time where society could decide to make a difference in the habitats of our existence, it is now. Development can no longer be a private inconsequential action that happens without the participation and involvement of the general public. Development needs to be a decision that takes the entire watershed into account. A plan should be developed to inhibit large quantities of ecosystem-sensitive land to be developed without the proper notions of sustainability at the forefront. This research proposes a methodology that is just one example of combining some of the necessary tools in developing a plan for development to support sustainability. The motivation is clear: by approaching watershed development from a simulation-optimization framework that mimics the pre-development flow regime, we might help to sustain these vital ecosystems for future generations to enjoy.

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