A Review of the Status of Current Critical Biological and Ecological Information on the Eurycea Salamanders Located in Travis County, Texas

prepared by
Aquatic Biological Assessment Team

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September 20, 1995

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ACKNOWLEDGEMENTS

Special thanks are due the guest speakers who participated in the information workshop. Their efforts added immeasurably to the success of this project. The outstanding efforts put forth by the ABAT members is genuinely appreciated. The assistance and expertise of Dr. Andy Price (Texas Parks and Wildlife Department) during the information meeting and field trip were of great value to the ABAT. Robert Hansen (City of Austin) and Dr. Larry McKinney (Texas Parks and Wildlife Department) demonstrated considerable patience during this often tedious process. –Ed.

INTRODUCTION

Following the decision of the United States Fish and Wildlife Service to publish rules proposing to list the Barton Springs salamander as endangered under the Federal Endangered Species Act, the City of Austin, Environmental & Conservation Services Department, and the Texas Parks and Wildlife Department, Resource Protection Division determined a desire for more information concerning neotenic Eurycea salamanders located in the Bull Creek and Barton Creek watersheds in Travis County. Subsequently, these two agencies entered into an interlocal agreement to establish an Aquatic Biological Advisory Team (ABAT) of nationally recognized experts in areas pretaining to aquatic invertebrates, stream ecology, geohydrology, amphibian ecophysiology, water quality management practices and impacts, to review the status of current critical biological and ecological information regarding the salamanders.

To the extent of their particular expertise the ABAT members were asked to review the status of critical biological and ecological information regarding neotenic Eurycea salamanders in Travis County, to possibly include:

• compiling and summarizing critical scientific data on the salamanders that may be instrumental to the development of conservation recommendations for the species.

• defining important information gaps that presently prevents development of effective factually-based conservation measures for the species.

• making specific, prioritized recommendations for short- and long-term research efforts for gathering critical missing data and to monitor the success of existing and future efforts to prevent habitat degradation.

• making recommendations to the extent practical on ecological and water quality benchmarks to strive for in order to protect the species.

• identifying existing probable or potential sources, land uses, practices, and water quality and quantity protection measures that are necessary to achieve the level of protection deemed necessary to protect the species.

• making general recommendations on ecological management practices, and water quality protection measures that are necessary to achieve the level of protection deemed necessary to protect the species;

The breadth of the ABAT members reviews were, to the extent that relevant data their expertise permitted, to encompass the following:

• the specific hydrological and hydrogeological regimes of the ecosystem which supports each salamander population.

• sensitivity of salamander populations (including salamanders in general) to variation in important water quality parameters. This should encompass both those which may have potentially catastrophic effects on the animals as well as those that may have low level chronic effects which might affect the viability of populations.

• dynamics of natural predator species that may take salamanders and of prey populations on which the salamanders may depend.

• population dynamics of the salamanders themselves and its relevance to the potential for extinction or local extirpation of populations.

• types of surface water contamination sources and controls in the recharge and contributing zones for springs supporting the salamanders.

• types of groundwater contamination sources and controls in the recharge and contributing zones for springs supporting the salamanders.

• measures to preserve existing hydrological regimes.

• protection measures in the immediate spring discharge areas that represent the salamander habitat.

The ABAT members were instructed to not review specific laws or regulations nor make recommendations regarding changes to such laws.

The ABAT was presented various reference materials in regard to the biology of Eurycea salamaders, regional geohydrology, stream ecology, water quality and quantity, and additional information on the Bull Creek and Barton Creek watersheds. The ABAT then attended an information meeting held at January 20-21, 1995 at the Wild Basin Preserve in Austin. This meeting was structured around presentations by regional experts on pertinent biological and ecological information and existing ordinances relating to the Bull Creek and Barton Creek watersheds (Appendix 1). The second day of the fact-finding meeting involved an aerial overview of the Barton Creek and Bull Creek watersheds and on-site visits to several key locations in those watersheds where salamanders occur.

Herein, is a summary of the general observations and findings of the ABAT, including their prioritized recommendations in regard to their specific taskings, and their individual reports in their entirety.

A REVIEW OF STATUS, RESEARCH AND MANAGEMENT OF TAXON VIABILITY FOR THREE NEOTENIC AQUATIC SALAMANDERS IN TRAVIS COUNTY, TEXAS

by

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for

Texas Parks and Wildlife

Report Purpose and Main Conclusions

This report reviews the status of biological, ecological and management information regarding three neotenic plethodontid salamanders found in Travis County, Texas. It 1) reviews the rationale for concern about salamander viability (Part A: Rational For Concern), 2) identifies important information gaps impeding development of conservation measures (Part B: Information Gaps), 3) recommends research measures needed to proceed effectively (Part C: Research Needs), 4) discusses specific ecological and water quality criteria needed to sustain salamander viability (Part D: Ecological and Water Quality Criteria), 5) reviews protective measures needed to sustain salamander viability (Part E: Protective Strategies) and 6) makes general recommendations about management for salamander viability (Part F: General)

Recommendations.

Enough information now exists to conclude the following about the status of two neotenic Eurycea salamanders in Travis County, Texas:

a. Based on a summary of existing scientific data on salamander ecology and ecosystem conditions, threats to salamander viability are both real and growing, but are understood much better in principle than in quantified, site- and taxon-specific terms.

b. Information gaps impede specific recommendations at several levels of salamander ecosystem understanding.

1) population genetics, dynamics and environmental tolerances, and community interactions defining future viability,

2) habiat attributes; including fluctuations, structural diversity and interconnectedness, that are optimum and intolerable for salamander viability,

3) aquifer attributes that determine the rates and forms off contaminant and other material and energy transport to salamander habitats,

4) watershed attributes that determine rates and forms of contaminant and other material and energy generation and transport directly to salamander habitats or to groundwater aquifers supplying salamander habitats,

5) airshed and global attributes that can contribute to material and energy changes in salamander habitats.

c. Research is needed to provide critical data needed for cost-effective management and monitoring aimed at sustaining salamander viability.

1) use of databases and mathematical models to organize existing population,

community, habitat, aquifer, watershed and global data relevant to salamander viability into initial syntheses useful for assessing critical research needs,

2) development of a suitable bioassay procedure for assessing salamander ecological tolerances to variation from optimum in present and potential habitats,

3) completion of research on development of artificial habitat for holding of salamanders threatened by imminent catastrophic events,

4) assessement of form and rates of watershed change associated with urban development, infrastructural degeneration, and corrective management actions,

5) collection of population, community, habitat, aquifer, watershed process, aquifer process, habitat suitability, community change and salamander population viability.

d. Only general recommendations can be made at this time for development of ecological and water quality criteria designed to cost-effectively protect salamander viability.

1) criteria should focus on what is necessary to sustain salamander viability,

2) criteria should be proactive, allowing analysis to identify harmful changes well in advance for remediation,

3) criteria should be sensitive and predictive indicators of threatening change based as much as possible on actual salamander tolerances and vulnerabilities (such as salamander bioassays based on subtle behavioral changes),

4) criteria should be integrative as much as possible to reduce the need for many expensive measurements,

5) criteria shuld serve to protect all community components supporting salamander viability.

e. There exist numerous potential threats to and protective strategies for sustaining salamander viability.

1) potential for catastrophic events, such as spills of toxic material into surface and aquifer courses leading to salamander habitat,

2) cumulative chronic affects of contaminants dervied from watershed and airshed sources,

3) short-term and intense affects of contaminants associated with storm pulses,

4) long-term climatic change,

5) physical destruction of habitat,

6) collecting and related direct human impacts,

7) introductions and other changes in supporting aquatic communities.

f. Ecosystem-based management strategies can be designed to protect salamander viability and should be used following more thorough evaluation of cost effectiveness and practicality.

1) development of an ecosystem management plan that incorporates all significant sources of threat to salamander viability,

2) development of a long-term management perspective with management and research action priorites established according to the level of threat to salamander viability,

3) interagency support of and contribution to shared databases and analytical models,

4) integration of ecosystem management for protecting viability of salamanders with ecosystem management for viability protection of other species in and above the Edwards Aquifer,

5) development of integrated and cost-effective mangement strategies designed to serve more than the one purpose of protecting salamander viability,

6) development of a crisis management plan that provides the rapid and appropriate response for transfer of salamanders to temporary holding facilities in case of catastrophic spill or other unforseen events.

Each of these main conclusions initiates one of five parts in the following report. Each part was developed in response to a series of charges made to the review team by the Texas Parks and Wildlife Department. All parts focus on needs for protecting the viability of the three neotenic salamanders in Travis County, but also consider closely related issues that may be most cost-effectively addressed through coordinated planning, research and management.

The definition of viability is an important precursor to defining the problem and appropriate management strategy. I essentially accept Shaffer's (1981) definition of viability

as that minimum population number required to assure a high probability of existence beyond the foreseeable future, despite natural events and foreseeable deviations from past ecosystem conditions. This definition allows quantifiable and rationale management decisions based on data obtained from each of the salamanders' ecosystems. It guides the search for relevant information pertaining to salamander viability. For the management problems determined here, sustaining salamander viability in the face of expected ecosystem changes, the rates and permanency of expected changes are major variables defining the foreseeable future. Past urbanization indicates that a 100-year planning horizon is a rational minimum time frame for planning strategy designed to protect salamander viability. That time frame is based on Travis County history, long-term natural periodicity, such as drought "cycles", and the length of time human caused changes have lasted in salamander habitat (e.g., Barton Springs Pool). The time frame for viability chosen here should place review recommendations in perspective. Planning, research and management recommendations presented in each section are not scheduled, but in all cases are expected to take place over a long planning period. However, the last section emphasizes the needs to plan carefully with the viability objective in mind and attempts to place general priority on different management research interests.

Ecosystems Orientation

The viability of neotenic salamanders in Travis County, Texas rests in effective management of ecosystems interactions within and among several hierarchial levels in ecosystem organization: population, taxon, habitat, community, aquifer, watershed, airshed, and biosphere. The ecosystem integrity needed to sustain the neotenic salamanders of Travis County involves ecosystem organization at most hierarchial levels. Population systems interact to form taxonomic systems (subspecies, species) and aggregations of different populations within the same habitat systems form community systems. The suitability of habitat systems for sustaining population viability usually depends on higher hierarchial-level influences, such as from aquifer systems, watershed systems, airshed systems and biosphere systems. Contemporary ecosystem concepts include human actions among the natural ecosystem interactions (Regier 1993). The concept of ecosystem used here emphasizes systems behavior, systems function, and the process that interconnects among living populations in communities and their abiotic environments. In this view, hierarchial organization of ecosystems determines certain basic attributes of ecosystems, which in turn contribute to sustaining salamander viability.

This review evaluates threats and their management at all hierarchial levels. At the population-taxon level, it reviews population dynamics and its relevance to salamander viability. At the habitat-community level it reviews salamander sensitivity to habitat change, including physical, chemical, and biological changes of chronic and catastrophic dimensions. It also considers predator and prey interactions as well as protective measures for habitats and communities. At the aquifer level, it considers the nature and preservation of hydrological regimes that greatly determine that habitat integrity necessary for supporting salamander population viability. At the watershed level, it considers hydrologic regimes, especially with respect to surface water quantity and contamination, and its impact on that groundwater

quality and quantity required to sustain habitat integrity. At the airshed-global level, it reviews observed and potential changes that could mitigate ecosystem management effectiveness at all lower hierarchial levels.

Threats to salamander viability and their management countermeasures may originate from any hierarchial level. Ecosystem interconnections not only contribute to normal functions supporting population viability, but also become pathways for propagating harmful effects. Although those threats and countermeasures that occur at the population and habitat levels may appear to be of the highest priority in first examination, events operating at other hierarchial levels may greatly constrain management focused too intently on salamanders and their habitats. Assurance of salamander viability therefore is facilitated by a hierarchial approach to understanding diverse threat sources, potential threat interactions, and coordination of effective management counter-measures.

Clear definition of systems "boundary" behavior is often challenging yet necessary for effective protection of rare taxa. Ecosystem boundaries are porous, allowing both supportive and antagonistic links to the environment. For example, the number and dispersal of physically discrete populations within the same taxon is an important concern when considering taxon vulnerability to pervasive threats. Apparently isolated habitats, supporting discrete populations and protected from all but the most pervasive threats, could in fact be interconnected parts of a single habitat system sustaining a single population that is vulnerable to less pervasive threats. Similarly, complete knowledge of habitat elements is required to assure sustenance of population viability. Parts of habitat systems may be only briefly occupied or potentially occupied by certain population members, but be essential for population viability. Thus for certain stream animals, including the Travis County salamanders, deep hyporheic interstices may intermittently but critically serve as population refuges when drought dries up surface flow.

Boundaries typically are drawn around ecosystems based less on ecosystem properties and more on the needs of ecosystem management. The concept of ecosystem integrity is related to the process of setting ecosystem boundaries for management purposes. In doing so, managers need to realize that those boundaries are in fact quite "porous", having many interconnections to other ecosystems within or outside their defined boundaries. Those managers focused on population dynamics within a single springhead will draw their ecosystem boundaries along springhead margins. Those managers may be inclined to enhance perceived boundaries with artifices that isolate the system from outside threats while unknowingly walling out necessary ecosystem process. In contrast those managers interested in taxon viability, such as the viability of the neotenic salamanders in Travis County, will seek that ecosystem boundary which includes all of the positively influential environment and connecting pathways to the salamanders, including aquifer, watershed, and areal pathways. Understanding of key ecosystem interactions is not only prerequisite to understanding a taxon's resource requirements and environmental tolerances, it is also prerequisite to effective ecosystem management. This report is therefore organized around major hierarchial divisions of salamander ecosystems.

Part A: Rationale for Concern

Based on a summary of existing scientific data on salamander ecology and ecosystem condition, threats to salamander viability are both real and growing, but are understood much better in principle than in quantified site-specific, and taxon-specific terms. The rationale for concern exists at all hierarchial levels of ecosystem interaction, starting at the population level and extending to global change.

Population-taxon

Each of two neotenic salamanders inhabiting springs in Travis County, Texas has a localized distribution and low total numbers. The newly described species, the Barton Springs Salamander Eurycea sosorum (Chippingdale et al. 1993a) is known to inhabit several closely grouped springheads in the Barton Creek watershed (Barton Springs Pool with several closely situated spring openings, Eliza Spring and Sunken Gardens Spring). The other taxon, in the genus Eurycea, is located in Bull Creek watershed, possibly Brushy Creek watershed, and nearby watersheds in other counties (Cedar Creek, Long Hollow Creek, Walnut Creek). The taxon is commonly called the Jollyville Plateau Salamander, but is not as yet scientifically named. Jollyville Plateau Salamanders inhabit some unknown fraction of up to 23 known springs in the Bull Creek watershed, although the habitat status of each spring is incompletely documented.

Other springs in the vicinity have been investigated without encountering the Barton Springs Salamander. Although there remains some possibility that the salamander taxa occur at sites other than known habitats (especially the Jollyville Plateau Salamander), existing documentation indicates they are quite locally distributed, with the Barton Springs Salamander the most locally distributed. Further investigation is not likely to significantly alter that conclusion.

There is no knowledge of pristine salamander densities. While estimates of existing densities are approximate and incomplete, the salamanders appear no where to be abundant. The combination of localized distribution and sparse density indicates a low to moderate total abundance. The largest number of Barton Spring Salamanders found at any one time in a 2-hour scuba search of Barton Spring Pool was about 150 individuals. The total area of suitable habitat is not precisely quantified, but is likely to be less than one or two hectares of surface habitat for each of the taxa. More critical than the total number is the uniformity of risk among all population numbers. Highly localized salamander distributions in habitat supplied by a common groundwater source is reason for profound concern where groundwater quality and quantity is threatened.

The two salamander taxa exhibit a mix of troglobitic and surface-dwelling characteristics (Sweet 1982, Chippendale et. al. 1993b), which suggest at least partial adaptation to either hyporheic or cave habitat. Although an apparent rapid decrease and recovery of population density in Barton Springs Pool suggests recolonization from other locations (Chippendale et

al. 1993a and b), the extent or source of recolonization is unknown, if indeed it ever occurred. Apparent recolonization could be a sampling artifact caused by random error and inconsistency in salamander sampling effort. If recolonization did occur, immigration may have been from adjacent hyporheic or cave habitat, rather than from other springheads. There is no conclusive evidence that salamanders move between springhead habitats via groundwater connections, even though their mixed surface and troglobitic characteristics suggest that they could do so where opportunities exist. Rapid transmissivity of water and fluctuation of groundwater turbidity in the Edwards Aquifer indicates a subterranean porosity that may be conducive to extensive subterranean movement of salamanders.

Because of statistical limitations, past surveys only suggest, and do not confidently confirm, that salamander numbers fluctuate. Fluctuations may be apparent only, caused by sampling error. If the fluctuations are real, they could be caused by birth rate and death rate responses to both natural and cultural ecosystem change and by migration between surface and subterranean portions of the habitat. Less is known about numbers of the Jollyville Plateau Salamander, but relatively few have been observed in each of the sampled springs.

In conclusion, little information exists to determine the extent to which salamanders in each springhead comprise self-sustaining populations. Neither is it possible to determine from existing information which parts of the total known habitat are critical for population viability and which, if any, are not. Although the relatively high abundance observed in Barton Spring Pool suggests that it is the most critical part of the total known habitat, statistical and ecological uncertainties do not allow the conclusion that it alone among the known springhead habitats could assure population viability. Less is known about the Jollyville Plateau Salamander, but it appears to be less vulnerable to a single pervasive environmental impact than the Barton Springs Salamander because their spring habitats are more widely dispersed in three counties.

Habitat-Community

The interconnectedness of the springhead habitats is a fundamental issue in determining which parts of the total habitat are most critical for sustaining population viability. The known occupied habitat of the three neotenic salamander taxa of Travis County are springheads and downstream spring-runs up to 400 meters below the springheads. Important parameters for gauging habitat suitability that sustains community viability in springs include discharge, ambient light, temperature, the riparian community adjacent to the spring, spring flow morphology, substrate characteristics (e.g., type, size, embeddedness, travertine precipitation), spring community composition, the contribution of surface runoff to or downstream from the spring head, and various human impacts. Appropriate maintenance of habitat water quality is of paramount concern (O'Donnell 1994) because amphibians appear especially sensitive to natural and synthetic toxic materials that enter the habitat either directly or from more remote parts of the ecosystem.

Direct impact to the springhead habitats has already been observed at Barton Spring

Pool and Eliza Spring, where pool maintenance activities (chlorine and water-jet cleaning) are suspected of causing temporary decreases in salamander abundance. Salamander numbers appear to have increased since new cleaning procedures were adopted, however. The most recent salamander counts at Barton Spring are well above the lowest counts observed under the old maintenance program. Statistical uncertainty, however, clouds any conclusions.

The most dependably occupied environment now appears to be closely associated with springheads where groundwater discharges to the surface from subterranean aquifers. The extent that suitable habitat radiates from the springhead environments remains to be quantitatively defined, however, and could prove to be important occupied habitat upon further investigation. Habitat extension downstream from each springhead is determined by the rate of habitat change from conditions tolerated by the salamanders. Although temperature is an obviously important parameter that changes as flow proceeds downstream, other habitat changes accompanying downstream flow may be important in presently unknown ways. Generally speaking, spring water conditions are sustained farther downstream in spring-runs with greater discharge and greater protection from thermal variation by canyon and riparian shade. Downstream suitability probably changes with seasons, being more suitable in cool seasons.

The salamanders apparently move quickly in response to habitat change because they have been found in intermittent surface waters soon after surface flow is reestablished. Whether they recolonize flooded stream channel from hyporheic interstices or from the cave systems behind springheads is unknown (Chippendale et al. 1993b). Price et al (1995) believed that the salamanders are adapted to runoff variation and, therefore, unprecedented changes from past runoff pattern may threaten viability.

The degree to which habitat extends "upstream" from springheads into subterranean environments depends on population tolerance to subterranean conditions, including substrate penetrability, the darkness, and suitable nutrition. Habitat also extends downward into hyporheic waters in the stream bottom debris. Depth of habitat is determined by factors similar to upstream subterranean habitat. Separate springheads may be linked in unknown ways via partially or totally tolerable subterranean habitat.

Some evidence indicates that subsurface habitat (hyporheic or cave) may serve as a refuge during drought. Based on the emaciated condition of salamanders believed to have survived in subsurface habitat during drought, subsurface habitat does not provide all of the habitat resources needed to sustain population viability. Nothing appears to be known about how deeply salamanders penetrate into hyporheic zone or other subterranean environments nor how much this varies among springhead habitats. The viability of each taxon is questioned because of habitat scarcity and rapid human-caused changes in each salamander's ecosystem. That change generally threatens habitat suitability in the springheads and spring-runs where the salamanders are known to live. Not all change is threatening, however; some natural fluctuations and human-caused changes may sustain viability. Formation of artificial pools many decades ago did not result in extirpation at the springs supporting Barton Springs

Salamanders. Each of the three springs was converted to some extent from a rheocrine (free flowing) form, to a holocrene (ponded) form. Even though the conversion of form was most extreme at Barton Spring Pool, the largest fraction of the taxon appears to exist there. Provision of additional physical cover in the form of non living debris and aquatic macrophytes is advocated for protection from predation.

Habitats of the Jollyville Plateau salamanders have not been developed like the habitats of the Barton Springs Salamander. The physical appearance of Bull Creek springs is little modified from pristine conditions, except for several springs that apparently were destroyed or inundated, based on USGS map data. Whether or not any were or remain suitable habitat is unknown. Inundated habitat could conceivably sustain salamanders, as at Barton Springs. No evidence has been presented for or against managing the physical habitat in the Bull Creek springs more like that in the Barton Creek springs, probably because there are too many unknowns, including effects on other spring community taxa. Apparently more salamanders have been observed in pools than in riffles, possibly because it is easier to see them in pools.

Amphibians in general seem to be especially vulnerable to commonly occurring toxic compounds (McCoy 1994, Pechmann and Wilbur 1994), such as various petroleum product constituents and pesticides. No specific toxicity information exists for the three Eurycea taxa in Travis County, however. At least one widely distributed food organism, amphipods, also are relatively sensitive to contaminants (Borklakoglu and Kickuth 1990). Few data exist to determine general habitat requirements (e.g., oxygen, temperature, salinity, food), as well as information about how much contaminant intolerance is influenced by variation in habitat parameters from optimum conditions. Existing data indicate only that salamanders tolerate some variation in concentration of nutrient, suspended matter (turbidity), and fecal bacteria.

The salamander communities are not well described. An assortment of aquatic invertebrate taxa occur in the springs, many of which may serve as salamander food. There is insufficient trophic data available to ascertain if certain taxa play exceptionally important roles as food resources or as predators. The rheocrine spring communities of Bull Creek seem to have lower vertebrate species richness than the impounded springs along Barton Creek. Spring communities often exhibit lower taxonomic richness than in larger-order streams (Vannote et al. 1980). Low taxonomic diversity may indicate low functional redundancy in the community and a higher likelihood that species loss from the community could cause major changes in ecosystem suitability for remaining taxa, including the neotenic salamander taxa of Travis County.

Certain invertebrate taxa in spring communities may be more sensitive to contaminants than the salamanders, and their loss could result in a new community stability that works either against or for salamander viability. Other taxa fed upon by salamanders may be less sensitive to contaminants and concentrate the contaminants to harmful levels in the salamander food supply. Diversity in the impounded springs appears to be greater, perhaps because of increased habitat size, increased spatial heterogeneity caused by springhead ponding, and introductions by humans. How this affects salamander viability is unclear, except that it has

not so far caused their extirpation.

The predation role of various taxa is vague. Most of the springhead habitats appear not to be inhabited by predaceous fish. Barton Springs Pool, the main exception, seems to sustain a relatively large salamander population despite fish predators. Cover may be the more critical element, especially for protection from fish (Sih et al. 1992). Many of the springhead habitats could be inhabited by invertebrate taxa that may prey on small salamanders including crayfish and various species in the Hirudinea, Hemiptera, Megaloptera, Odonata, Coleoptera, and Trichoptera. Habitat structure, including aquatic vegetation, and cryptic salamander behavior probably play important roles in determining predation effectiveness. Cannibalism also may be affected by habitat structure (e.g.,intersticial sizes and locations) in presently unknown ways.

Aquifer

The continued habitat suitability for spring communities including neotenic salamanders, depends on physical, chemical and biological conditions in the aquifer supplying groundwater discharge. The quality and quantity of groundwater sustaining spring flows depend in turn on events in the surface watershed. Past observations indicate that Edwards Aquifer spring discharge and water quality parameters were variable, responding to highly variable precipitation (O'Donnel 1994, Bowles and Arsuffi 1993). Because the salamander taxa are adapted to historic habitat conditions, their viability may depend on sustaining certain historic patterns of groundwater variability that are only partly understood.

Aquifers supplying water to springhead habitats occupy karst topography. The spring habitat (or habitats) of the Barton Springs Salamander are located at nearly the lowest elevation in the Barton Creek Segment of the Edwards Aquifer. Flow will be sustained there longer than in other parts of the aquifer. Water transmission through the limestone conduits of the Edwards Aquifer is believed to be relatively fast (Slade et al. 1985) and unfiltered (EPA 1990), as is often observed in karst regions. The groundwater aquifer is shallower in the Jollyville Plateau area and water is transmitted relatively rapidly (between 33 and 328 feet/year) according to the Texas Water Commission (1989). The Edwards limestone in the Jollyville Plateau area is relatively thin and relatively free of major faults (Woodruff 1985) compared to the Barton Creek Segment. In the Jollyville Plateau segment, the springs serving as habitats emerge from the base of the Edwards limestone and from fractures and faults in the limestone. Some groundwater may be contributed by the underlying Trinity aquifer during extreme drought. Groundwater appears to flow from the San Antonio Segment of the Edwards aquifer to Barton Springs during severe drought.

Differences in aquifer geology in the Bull Creek and Barton Creek watersheds indicate somewhat different structures of threat pathways to springhead habitats. Major pathways to the Barton Creek springs are large faults leading from Barton Creek. Fissures are smaller and more diffuse in the Jollyville Plateau Aquifer (Price 1995). Aquifer draw-down seems to be less threatening to the Barton Creek springs where the aquifer is relatively thick and the springs

are at low elevations.

Watersheds

Threats originate mostly from activities associated with urbanization and materials transport. Both Barton Creek and Bull Creek watersheds are deeply dissected plateaus with moderate to high slopes between plateau and creek bottoms. Runoff originating on the plateaus contributes to flashy stream flows in the intermittent tributaries and perennial creeks. Soils are generally thin and infiltration comprises a small fraction of the aquifer recharge. The main pathways for aquifer recharge are limestone fractures in creek beds, most of which are imprecisely located by gauging changes in discharge at different points in the creeks. Surface water entering the creek bottom fissures undergoes relatively little filtration by soil infiltration and percolation. The Barton Creek Segment of the aquifer appears to have larger faults and a larger fraction of recharge via creek beds than the Jollyville Plateau Segment, but more complete analysis of Bull Creek watershed remains to be published (Price 1995). Among the various perennial streams in the watershed, Barton Creek appears to most influence spring discharge and water quality at Barton Springs.

Fractions of both Barton Springs and Bull Creek watersheds have undergone urban development. In the Barton Creek watershed, urban area occurs mostly in the lower elevations of Barton Creek nearest to the three spring habitats. That area has been developed for several decades. Septic systems, sewerage and other infrastructure is aging. About 3 to 4% of the watershed recharge zone nearest Barton Springs Pool has been developed. Water quality data are, however, too variable to tell if water quality at the spring habitats was associated with past urban development in Barton Creek watershed. Because only 15% of the recharge is estimated to be from small tributaries and infiltration, and a small fraction of the recharge zone has been developed, the increase of impenetrable surface probably has not significantly changed groundwater discharge with enough to measurably effect salamander viability. Lack of data indicating negative effects from urban watershed near the Barton Springs Pool is insufficient reason for concluding no urban effect, however. Other than sampling variation, specific aquifer structure could be a mitigating factor that does not necessarily extend to other development areas.

Some surface runoff can flow directly into Eliza Spring and Barton Springs Pool from the surrounding park area, possibly transporting contaminants into the spring pools. Areal transport of locally produced contaminants (e.g., dust from tire erosion) also may occur but is locally undocumented.

Nearly 30% of the Bull Creek watershed is developed, mostly with residential housing and related services in the watershed at elevations higher than the springhead habitats. Even though at least some of the springheads are protected by overhanging ledges, much of the downstream habitat may directly receive contaminated surface runoff from roads, roofs, lawns, parking areas and other urban development. Whereas Barton Springs aquifer dynamics are relatively well described, less is known about the Jollyville Plateau aquifer supplying spring

habitats for the Jollyville Plateau salamanders.

The two watersheds are to various extents occupied by sewer lines, gas lines, septic tanks, fuel oil tanks, roads, shopping malls, lawns, industrial development, and grazed land. The Barton Creek watershed is more rural than the Bull Creek watershed, but is crossed by roads bearing heavy commercial traffic. Some of the watershed is grazed.

Urban growth in the Barton Creek watershed has occurred over the past 50 years, but the present and future rate of growth is unclear. Urban growth (fractional increase of watershed developed) in the Bull Creek watershed has been rapid by comparison to Barton Creek watershed, but the present and future rate of growth change in the watershed is unclear. There are plans to develop Bull Creek watershed relatively rapidly (Price 1995). Other watersheds supporting Jollyville Plateau salamanders also are undergoing development at unknown rates except for wilderness protection on Cedar Creek, which includes several spring habitats harboring an unknown number of Jollyville Plateau salamanders. Although metropolitan growth rates are anticipated to remain relatively high, the growth in both watersheds is not documented well enough to discern the extent to which the two watersheds deviate from the general trend, if any.

Airshed-Biosphere

There appears to be little documentation of airshed and biosphere related threats that could influence habitat suitability and habitat management. The identified sources of habitat quality change emphasize waterborne transport from various origins. Yet local and more remote areal transport of harmful substances is possible and may be likely (e.g., Eisenreich 1981). Urban dust and precipitation is contaminated by numerous potentially harmful agents (Moriarty 1988). Such contaminants may be transported long distances far from municipal control. Toxic metals, synthetic organics, acids and nutrients have been documented to be transported aerially and deposited wet or dry either directly into habitats or indirectly into their watersheds.

Biosphere level changes are suspected with good reason (Carpenter et al. 1992), although the extent and distribution of effects remains to be confidently defined. Ozone depletion and atmospheric warming are the more widely discussed phenomena, which could prove to influence salamander viability. Changes in ultraviolet radiation and atmospheric temperature, if they occur, could alter salamander tolerances to other habitat changes.

Part 3: Information Gaps

General Comments

Information gaps impede specific factually-based conservation recommendations at several levels of salamander ecosystem understanding. Only some of those information gaps are now apparent. More will become apparent as ecosystem understanding increases. Greater quantification of viability issues is needed to most cost-effectively address protective measures. Systems interactions among biosphere, airshed, watershed, aquifer, habitat, community, taxon, and population processes are reasonably well understood in principle and as broad conceptual models. Much less certain, however, is application of that conceptual knowledge to specific circumstances, such as those influencing the population viability of the three neotenic taxa in Travis County springs. Those system elements supporting population viability for the three salamanders are, for the most part, imprecisely defined. Although this is enough to warrant great concern for salamander viability (O'Donnell 1994, Price et al. 1995), specific threat pathways and impacts remain to be clearly defined.

While the general ecosystem links to salamander populations have been defined (Chippendale et al. 1993, O'Donnell 1994, Price et al. 1995) and general trends regarding ecological change are apparent in the salamander ecosystems, the contributions of ecosystem processes and rates determining salamander population changes are not quantified. With a few critical exceptions, we are uncertain as to the specific tactics needed to preserve population viability in both watersheds, while not incurring unnecessary costs. More information is needed at each level of ecosystem influence suspected of contributing significantly to salamander fate and the role that management should play in determining that fate.

One of the more foundational research strategies for identifying the most rewarding research conduct for solving complex systems-based problems is development of analytical models that can organize existing information into a more predictive synthesis. Model development is facilitated by database management that organizes data in three-dimensional space and time. Geographical Information Systems (GIS) provide database management capability.

The process of model development often reveals significant information gaps as the model is specified. Through sensitivity analysis, appropriately designed mathematical models can be turned on themselves to identify weakness in ecosystem management understanding. Model development therefore is a strategy for rigorously identifying information gaps and cost-effective research.

The most useful models, however, are expensive to develop and may be best developed to address a number of viability issues simultaneously. Trends indicate, for example, that the integrity of many spring communities and numerous taxon viabilities are or will be threatened by development in and near the Edwards

Plateau. A coordinated regional approach addressing the multiplicity of emerging issues seems wise, both for database organization and for developing mathematical models. Certain information gaps, however, are presently obvious, they are indentified subsequently in hierarchial categories.

Population Level Information

At present, precise statements cannot be made about salamander population trend rates and probabilities for persistence or extinction. No habitat suitability or taxon viability models now exist to organize known knowledge into quantitative analysis for the salamander taxa. It seems fair to say, however, that threats to salamander viability are likely to grow especially quickly in the Bull Creek watershed. Whether threats are imminent or far-future has much to do with the strategy used to protect salamander viability.

Present information indicates that none of the two salamander populations are doomed regardless of management action. Certain decisions need immediate attention in order to protect the taxa in Travis County from uncertain catastrophic events within salamander ecosystems, even if present risk turns out not to be extremely high. Once those decisions are carried out, time should be available to more precisely identify critical information gaps and conduct appropriate research leading to more thoroughly protective and cost-effective management for both salamanders, and perhaps other related taxa occurring throughout the region.

Of critical importance in refining the degree of threat that exists is improved understanding of salamander population attributes, dynamics and tolerance of environmental change. The taxonomic description of the Jollyville Plateau Salamander needs to be confirmed through peer-refereed publication. Distributions are incompletely described, especially for the Jollyville Plateau Salamanders. Distributions within habitats are not clearly enough understood to accurately assess threats.

Except through analogy to a few other salamander species, little is known about population status, including those traits that help determine the viability of the Travis County taxa. There is no specific data on age distributions, age at maturity, sex ratio, fecundity, egg hatching success, and mortality in different life stages. There is little information relating size-frequency distributions within populations to population dynamics. Only approximate estimates of natality, mortality, emigration and immigration are available for input to population models for analysis of various risk factors. Only uncertain indicators of the relative contributions of each site to population viability exist. Because these data do not exist, there is little understanding of salamander resiliency following temporary harmful setbacks or recovery rate following reintroduction.

The numerical dimensions of the populations are not precisely known. Relationships of salamander counts to estimates of salamander population number or density are vague. It is not known how far into subsurface environments occupied salamander habitat occurs or

how densities change with substrate depth and other habitat characteristics. Although many spring habitats have been visited, the population status in each habitat is only generally known or is unknown. All possible habitats have yet to be checked for salamander occupancy using rigorous sampling techniques. There is little understanding of the relationship between salamander density and reproductive success, especially the point of decreasing density at which reproduction entirely fails.

Because numbers and population dynamics are not well known, there is insufficient information to estimate the effects of intense sampling or removal of salamanders for experimentation or other research purposes. In the process of developing better understanding of salamander abundance, habitat needs and tolerances to change, it is especially important to minimize the potential negative effects of research activities. To that end, there appear not to be available at this time either biological models or mathematical models designed specifically to test population perturbation for aquatic plethodontid salamanders. Until the understanding needed to construct such models is provided, the most effective management strategy is to assume that all existing populations and habitats must be protected to sustain taxon viability. This uncertainty in understanding limits management options that may ultimately be more cost-effective.

Habitat

Clear definition of habitat is needed to: 1) provide estimates of population resilience to changes in any one part of the habitat, 2) define population vulnerability to change occurring in various habitat parts, 3) provide insight into the physical pathways traveled by threats to taxon viability, and 4) provide insight into the value of habitat parts as refuge from catastrophic contamination or other environmental threats. Because ecological boundaries for salamander habitat are incompletely defined, it is difficult to evaluate the risks associated with habitat exposure to various threats.

Individual springheads may or may not be interconnected with habitat suitable for at least intermittent occupancy in hyporheic or cave environments. Landscape elements adjacent to the habitat may be integral to habitat function in incompletely understood ways. The riparian community both physically and biologically influences habitat condition affecting light quality and organic loading that may support salamander habitat needs. Land area draining immediately into the spring runs through surface and subsurface flows also is so intimately connected with occupied habitat that, from a management standpoint, it may be best considered part of the habitat system even though it may be rarely if ever actually occupied by the salamanders.

Of immediate concern is identifying what can be done to protect salamanders faced with imminent harm, including temporary or permanent relocation to natural or artificial habitats. Although some progress has been made in developing suitable artificial habitat, the habitat needs of the three taxa are incompletely defined. Only rudimentary habitat tolerance data exists for the two salamander taxa, based on generic knowledge about other, usually

distantly related, amphibians (McCoy 1994, Mahoney 1994). More specific knowledge is needed about optimum conditions and tolerated ranges for a variety of common habitat attributes and probable contaminants. In developing tolerance understanding, it is important to first use waters within the range of background habitat conditions including (but not exclusively) temperature, oxygen, calcium, salinity, and pH, and to concentrate on the extreme condition inhabited as much if not more than the optimum or average conditions inhabited.

Related to information gaps about tolerances, little is specifically known about natural habitat suitability of neotenic salamanders in Travis County. Only limited quantification of certain habitat parameters exists such as for flow rates, temperature, oxygen, salinity, suspended solids, pH, and ionic composition of the most common ions (usually calcium, magnesium, sodium, potassium, chloride, sulfate, bicarbonate, carbonate and silica). Most of the available data are from the Barton Springs Pool. The structural features of habitat are best documented for the Barton Springs Salamander. Only the most general information exists for other springs supporting the two taxa. Important substrate variables include rock, wood and leaf cover, substrate embeddedness by travertine or compacted sediments, extent of subsurface interstices and fissures, and the water quality in those habitats. Nothing seems to be known about how well groundwater moving from the springhead mixes with hyporheic water and the extent that all habitat is equally affected by aquifer quality and the quality of surface flows moving through the system.

Little information is available about the ability of salamanders to detect and avoid harmful habitat change by retreating into hyporheic recesses or backwater areas, as they may do when storm flows carry contaminants through occupied habitat. Little is known about variation in oxygen and temperature from surface flows into the intersticial water of hyporheic environments. It is not known whether springheads form isolated or contiguous habitat, either through downstream confluences or upstream cave systems. Thus it is not known how much individual spring habitats may be recolonized from other springheads following local depletions or how much the interconnections may act as routes for harmful agents.

Not much is known about the salamander communities. Although literature indicates that salamanders are generalist feeders within size ranges available, this has not been confirmed for the two neotenic taxa. It is not known how habitat variation, especially in subterranean habitat, influences the efficiency of food consumption by salamanders, the extent food exists in subterranean habitats, and the extent it provides refuge from predation.

Sources of mortality are imprecisely identified. Relative losses from starvation, predation, and lethal physical-chemical conditions are unknown; the importance of community integrity in sustaining the populations is therefore unknown. Physical-chemical condition of the habitat may be the overwhelmingly important factor, especially if salamanders are among the most sensitive of taxa to physical-chemical variation from optimum conditions. However, relative sensitivities of community components are only generally known. Although biodiversity appears low in most of the spring habitats, the species dominance and its stability in sustaining community integrity are largely unknown. Less may be known about the

susceptibility of other community members to physical-chemical changes in habitat than is known for the salamanders. Because habitat needs and habitat interconnections are not clearly defined, a clear protocol for protecting habitats has as yet to be completely developed. No habitat suitability or population viability models as yet exist to aid decision making nor rankings of the relative importance of various habitat features in sustaining population viability.

Aquifer

The aquifer is the primary supply of suitable water for salamander habitat. Proper groundwater discharges and quality are likely to be essential for sustaining population viability. The aquifer could change gradually or catastrophically by alterations in groundwater discharge and water chemistry. Lethal threats are possible through either intermittent (possibly catastrophic) or chronic exposures. Drought periods are most critical for understanding of water quantity and water quality effects in salamander habitats because groundwater discharge quantity and environmental impacts are likely to be interactive.

There is no evidence, however, of an analysis of existing data that extrapolates the effects of low groundwater storage on spring flow, suitability of subsurface habitats as refuges, and chemical concentration, including, importantly, salinity. Although qualitative understanding exists for groundwater withdrawal effects, no predictive models exist to clearly relate withdrawal, surface water diversion, land use patterns, and risk factors to groundwater discharge and quality in the salamander habitats. Connections to other aquifer segments or other formation aquifers are known, but the effects of cultural activities in those remote aquifers are not quantitatively defined, especially for critical drought periods.

The transmissivity of groundwater is only generally estimated within the vicinities of neotenic salamander populations in Travis County. Specific transmission routes between salamander habitat and sources of groundwater contamination are not well defined. Variation in transmission rates may be large, depending on cave-system development and sedimentation within the cave system. Some of the most important potential routes of contaminant entry from source to habitat need to be examined for transport time and attenuation, dilution, and retention in the aquifer. The effectiveness of the aquifer in mitigating or magnifying potentially harmful water quality effects is not well understood. It is not known to what extent the aquifer dilutes, filters, sorbs or chemically alters material contents of surface waters supplying aquifers that flow into salamander habitats. This requires sustained monitoring of aquifer inflows and groundwater discharges into salamander habitats.

Watershed

Watershed process is better documented than most other ecosystem processes for the salamanders. The general sources of water are known and many of the sinks into the groundwater flows have been localized if not exactly located. Enough information now exists to recognize that high threat situations occur where contaminant transport paths cross Barton

Creek. The highest risk sites, such as at L360, need immediate engineering to divert and hold contaminant spills.

Potentially harmful water quality change has been correlated with urbanization (Veenhuis and Slade 1990). What remains unknown is a more quantified estimation of the relative flow contributions from different landscape types and the quality of water departing from those different types, including its suitability for sustaining salamander populations. Because material content of stream flow usually increases non-linearly with stream discharge, there needs to be further investigation of storm-event runoff and quality as it relates to stream quality and groundwater quality emerging in the springhead habitats.

Groundwater contamination by surface runoff into wells is generally recognized, but is not quantified in terms of type, sources and amounts of contaminants. Possible leaks from sewerage and septic tanks, fuel lines and industrial storage facilities are grossly quantified, but there is little knowledge of distributional biases. It is not known if the leakages are random within sewer-system age categories. The probability of leakage also has not been categorized by age of the structures or the criteria by which they were constructed.

Relative rates of anthropogenic change in the region are documented, but have not been more specifically analyzed for each of the watersheds. Although observations of municipal growth indicate worrisome trends, more specific trend analysis is needed for the watersheds in question. More important still, is an analysis of the rate and location of proposed urbanization in the two watersheds based on development plans. Where plans provide insufficient information, the needed data should be identified and provided by the developers-regulators.

Global-airshed: Local governments and interest groups may be able to do little by themselves to mitigate atmospheric changes, except through general education and influence on state and federal authorities. Because such influence and education has more impact if atmospheric conditions are shown to be effected locally, it is advantageous to locally monitor precipitation and dry deposition. What ever existing data exists needs to be integrated into the perspective of salamander ecosystems. This information also will help decision-makers define appropriate management as the relative role of global process in threatening aquifer ecosystem integrity becomes clearer.

Although global and major airshed study is beyond the scope of local authorities, the best policy analytical models for the watersheds and aquifer supplying local salamander habitat should be able to analyze for projected global effects as results of more certain global analysis become available. Obvious global factors include temperature, pH, ozone related electromagnetic radiation change, and harmful material composition and loads in dry and wet precipitation.

Part 4: Research

Population-taxon

Research is needed to provide critical data for cost-effective management and monitoring aimed at sustaining salamander viability. Research needs extend to all hierarchial levels, but with certain important exceptions research urgency is greatest at population and habitat levels. The main exception is identification of travel routes for catostrophic spills. Distribution study of the two taxa needs completion. While this is most evident for the Jollyville Plateau taxa, remaining site possibilities also need to be investigated for the Barton Springs Salamander. These distribution studies are prerequisite for most other research needs. Investigators need to gain access to all possible habitat by whatever legal means possible.

A precursor to other research is research and development designed to mitigate the negative effects of research on the viability of the neotenic salamanders. Salamander centered research should use least-damaging methods, emphasizing biological and mathematic models in place of the scarce species, whenever practical. A biological model is a test organism that serves as a surrogate indicator of ecosystem suitability for rare species; in this case, the two neotenic salamanders in Travis County. An appropriate test organism is likely to be one of the more abundant neotenic salamanders in the Edwards Aquifer spring communities. The test organism may be useful for analyzing threats to a number of other salamander taxa in the Edwards Plateau area. Identification of a suitable test organism will be facilitated by completion of neotenic salamander taxonomic studies conducted by Chippendale et al. (1992).

The risks of catastrophic damage to natural habitat is going to be time consuming to refine and may never be precisely estimated. Until study determines otherwise, managers must assume that potentially damaging events could occur at any time. Artificial habitat can be used to temporarily hold members of salamander populations when a catastrophic event occurs.

Preliminary research in progress on artificial habitats (Roberts et al. 1994) needs to be accelerated and completed as soon as possible, with attention most paid to temporary holding of salamanders. More elaborate artificial habitats may ultimately be used to house self-sustaining populations, perhaps in cooperation with zoos or universities. Emphasis, however, should not be placed on artificial habitats as the sole or main support system for a taxon, because of high risks of artificial habitat failure and longterm unknown genetic effects.

Surrogate test organisms should be used to study tolerance to variations of critical habitat variables including temperature, oxygen, salinity, food and other fundamental habitat characteristics. This research may be most cost-effectively integrated with development of artificial habitat and viability models. The suitability of the artificial habitat and accuracy of the tolerance data for the threatened taxa can be tested using low numbers of threatened taxa, then refining results as needed. This approach minimizes damage to the rare taxa. Artificial habitat will be most useful for managing the impact of catostrophic events.

It is critical to evaluate salamander tolerances to variation from these habitat conditions most likely to sustain salamander population variables. Because we expect that many aquatic salamander taxa will react similarly to water chemistry and contamination, the same common species used to develop artificial habitat should be used to assess contaminants toxicity and other tolerances. Comparative studies should be done subsequently to identify differences, if any, that exist between each of the scarce taxa and the common species. Mathematical simulations of population demographics and dynamics used in place of actual salamander populations would organize existing data into a predictive synthesis while minimizing damage to the rarest taxa. Such models can be developed from existing mathematical structures, even from models developed for entirely different kinds of organisms (Kitchell et al. 1978), as long as all of the key parameters are included or can be added. Existing models can be calibrated with data obtained from closely related but common species wherever such data do not already exist. Models are useful for examining the effects of uncertain data on outcomes of concern--in this case the viability of neotenic Eurycea taxa. Research can be prioritized to focus on those parameters with greatest possible impact.

Bioassay procedures for behavioral end points have been developed for other amphibians (Steele et al. 1989) and invertebrates similar to some in the salamander communities (Borklakoglu and KicKuth 1990). The procedures should be applicable to salamanders or other spring community organisms. Behavioral toxicity tests allow identification of threatening changes in time to prevent lethal changes. Because the threatened animals are the most integrated indicators of harmful change within their ecosystem, monitoring non-lethal behavior in their habitats may be the best way to identify harmful change in the earliest stages without loosing the population. Once developed, live indicator animals can be exposed to recovering habitats or habitats considered for reintroduction, to test habitat suitability. They also can be exposed to various dilutions of runoff water from different land-use areas to biomonitor for sublethal tolerances. Both chronic and short-duration exposures to altered environments need to be tested. Such tests should be based on conditions occurring in spring habitats during and following runoff events and between (chronic exposure) storm events. Bioassay organisms can be used to test tolerances to runoff quality from various sources and at various dilutions predicted in groundwater mixing. Treated runoff can be tested similarly. Mass balance models should be developed to estimate the dilution capability for each of the major threat source locations.

Defining relationships between apparently separate spring head population dynamics and genetic interchange falls into a research need in this hierarchial category. The evolution of distinct genetic traits in each of the salamander taxa indicates past reliability of habitat conditions sustaining population viability. That apparently separate springs support genetically similar populations within each salamander taxon indicates either unknown existing or recent past connections among habitats enabling population interchange. Understanding of those connections may be difficult to develop, but would be helpful for managing genetic viability in each of the taxa. Management decisions about sustaining or preventing interconnections depend on this information.

Populations with low abundances within individual habitats and patchy distribution of habitats may have within-habitat and between-habitat characteristics that need to be defined to accurately estimate threats to population viability. This is difficult and potentially damaging research for scarce populations that may spend substantial amounts of time in subterranean regions. For those reasons, such detailed study of population distributions within habitats should focus first on closely related, and abundant taxa. Population natality, mortality, immigration and emigration are important parameters, but are difficult to measure in a low-density situation. Complete understanding requires knowledge of initial population size in all parts of the habitat, age, food selection and consumption rates, food conversion to growth, growth rate, maturation rate and size, female abundance, sex ratio requirements, fecundity (eggs/female/year), and various important sources of mortality and routes of immigration and emigration.

Habitat-Communities

Springhead and downstream spring-run sampling of discharge and water quality should begin soon. Sampling intensity needs to be linked to flow response time following rainfall events. Between rainfall events, during base flow, a relatively small number of samples may be needed, depending on the observed variances. Pilot studies are needed to define the required sampling intensity for each runoff condition monitored, once the desired precision is identified. From data gathered in pilot studies, correlations among diverse parameters can be estimated and where high correlations exist, sampling can be adjusted to reduce costs in extended monitoring.

Larger numbers of samples are likely to be needed during the rainfall response periods when short-duration but dramatic habitat changes are most likely to occur. Therefore, discharge behavior should be tracked with respect to rainfall in the watersheds and sampling intensity varied appropriately. The precision should be based in part on salamander tolerance ranges and therefore indicates a need for simultaneous tolerance studies during the habitat pilot studies. Variation among and between springs should be assessed to estimate the most cost-effective monitoring approach for desired precision. Because intense monitoring may be prohibitively expensive, research design may need to concentrate on priority habitats, which serve as models for comparison to less frequently sampled sites. Prioritization could depend on the perceived importance of the site for sustaining populations, vulnerability to threats, and ease of access.

Special attention should be paid to the possibility of forming springhead and spring-run pools and adding physical structure as possible ways to increase population density in some of the habitats. Physical and chemical habitat variation should be measured in conjunction with studies of salamander distributions in habitats before modifications, if any, are made. Especially significant are measures of hyporheic intersticial structure and chemistry, including oxygen concentration and downstream extent of appropriate habitat conditions. Both may be altered by morphological modification of habitats. Research should be directed not only at salamander tolerance ranges but at defining optimum habitat conditions that can be targets of

management activity, such as habitat morphology and riparian condition.

More knowledge of salamander communities is needed to typify present biotic integration for future comparison to monitored trends. Measures of taxonomic diversity and functional ecology are needed especially with respect to the trophic ecology of the two salamander taxa. Again, using the test organism as a surrogate indicator, food selection should be assessed to determine the extent to which food-item taxa and size are selected. Some assessment of relative food item availability is needed.

Indicators of food item production, such as mean size and biomass of invertebrates within suitable size ranges should be assessed, with a taxonomic breakdown into at least morphologically and behaviorally similar groupings. Vertical distribution of food in the hyporheic substrate is needed to assess the suitability of the hyporheic zone. Predators need to be identified. Research on the relationship between cover and interstitial refuges and predator activity should be useful for managing habitat structure to favor salamander protection.

Although some common salamander taxon may be the best biotoxicity test organism for identifying vulnerability to direct threats, it may prove more cost-effective ultimately to seek out a sensitive and more widespread community member of Edwards Aquifer spring-head communities to gauge habitat quality change. Amphipods or other spring invertebrates may be an appropriate test organism for evaluating the integrity of salamander communities.

Potential contaminants need to be monitored, including selected metals and synthetic organic compounds. One of the more organized and cost-effective ways to address such a problem is through development of a mathematical model based on existing data and data obtained from abundant similar species. Such a model is first developed from whatever information can be gleaned from the scientific literature. Through the modeling process and subsequent sensitivity analysis, research deficiencies can be prioritized based on the effect of parameter uncertainty on the uncertainty of estimating salamander viability. This process can help reduce the need for large organism sample sizes that could ultimately reduce or elevate population viability.

In refining parameter estimates using salamanders as experimental animals, abundant but closely related species should be chosen to work with whenever feasible, to reduce damage done to the rare species. Once again, when it becomes critical to experiment with the rare species, the numbers required may be controlled by focusing only on those most relevant parameter differences identified in the models.

Links between salamander population dynamics, threatening conditions and positive management actions are needed to predict risk and its management. An assessment of population viability should be made using demographic and habitat suitability techniques (Shaffer 1981).

Aquifer

Monitoring of springhead habitats when combined with certain watershed monitoring should help determine the extent that water quality and quantity entering aquifers is altered by aquifer processes before it reemerges from the aquifer at the springheads. Where feasible, water tracer studies should be used to identify the time lapsed between sites using dye injection or other tracers. This appears to be especially relevant for the Barton Springs segment of the aquifer, because of the general relationship described between Barton Creek sinks and Barton Springs. As an alternative, especially in Barton Springs, water sources and material transport times may be tracked by simultaneous monitoring of storm events, sink water quantity and quality and spring discharge quantity and quality. Lag times, attenuation amounts and dilution-retention of materials can then be estimated through regression and mass balance analysis of watershed inputs to the aquifers and spring-flow outputs.

It appears as that complete taxonomic description of the Eurycea neotenes species group will result in numerous relatively rare taxa in the Edwards Aquifer, a number of which are likely to face threats similar to the three Travis County taxa (Chippendale et al. 1993b). Because of that large number of possible candidates for protective action, research coordination and cooperation appears to be the most cost-effective approach to analyzing aquifer related impacts on spring communities. Development of a common biological model for analyzing habitat impacts may be suitable for more than the taxa of concern in Travis County. Similarly, development of artificial habitats may be suitable for any of a number of salamander taxa that are likely to be of concern in other counties overlying the Edwards Aquifer. Because many of the springs occur at elevations within a few meters of each other, a widespread uniform decrease in aquifer water level is a comprehensive threat, and therefore of more concern than local threats to individual habitats. Available well-level data should be analyzed for aquifer-level trends and groundwater quality trends, and their relationship to possible local and regional sources of water level change. In the future, existing wells should continue to be monitored for water level and water quality spacial variation and variability, watching for trends.

Again, models are a useful tool for organizing information for analyzing policy impacts. In this case, projected groundwater development or water injection effects would be the object of analysis, as they relate to the discharges of salamander critical habitats and potentially other habitats in the aquifer. For long-term cost effectiveness, it would be desirable to make watershed models and aquifer models compatible. A database management system that stores and retrieves data with respect to elevation, latitude and longitude coordinates would facilitate model development and other integrative activity.

An advantage to development of an aquifer-wide model is that local governments and public interests can differentiate local impacts and local responsibility from remote impacts and responsibility. Many of the attributes of an aquifer-wide model would be similar to the local watershed model, but perhaps with less information density because of less average cultural impact over the entire aquifer than occurs locally in the two salamander watersheds. By taking

the larger perspective, local decision-makers can estimate more realistically the effectiveness of local actions before expensive and possibly ineffective actions are taken. Investing locally in salamander protection will be unwise if more remote activities are in fact determining the fate of the salamanders. Because such research and development probably extends beyond local impacts, local governments may want to encourage regional and state governments to play a coordination role and a supportive role in conducting such research and development.

Watershed

Although data presently exists on traffic rates, additional data on the transport of hazardous materials are needed to determine the fractions of traffic carrying hazardous materials. Hazardous materials should be classified by type, if these data are not already available. This type of data is needed to make rational decisions about traffic control or structural modification of the watershed. However, where high risk rates are obvious, such as at the L360 bridge over Barton Creek, engineering solutions should be promptly investigated and installed.

Additional research of urban development effects is needed. Existing information about the effects of various urban developments on watershed flows needs synthesis to estimate diversion, infiltration and evapotranspiration effects. Although knowing something about average impenetrable surface is a start, and indicates a growing threat to persistence of suitable salamander habitat (especially in the Bull Creek watershed), more needs to be known about how each type of development contributes to watershed process, and more specifically with respect to the Bull Creek and Barton Creek watersheds.

Just as for salamander population research, a cost effective way to organize existing data for risk analysis and analysis of further research need is by means of mathematical models. Numerous watershed models exist and some treat urban process. Thus there is a base to start from. If GIS type databases are organized as advised, serious consideration should be given to integrating the databases with model development. It will be most cost effective in the long run to invest in a GIS approach that is compatible with larger scale efforts (regional or state level) either in progress or planned.

Models should focus on parameterization that will allow optimal urban development to occur given the objective of sustaining salamander population viability. Examples of development type include dense, moderate or sparse residential development, retail development, transportation infrastructural development (roads, airports, rail and related services), waste treatment system development (sewage transport and treatment, surface runoff treatment, utility development (gas lines, electrical services), light industrial development (heavy on service and light on material transformation and transport), and heavy industrial development.

Parameters of importance include, but are not limited to, the effects of each development type on fractions of surface and subsurface flows, quality of surface flow

contributing to subsurface flow, quality of surface flow directly entering salamander habitat areas, rates of subsurface transport of contaminants toward habitats, and dilution and removal of contaminants during transport. Quality indicators of importance are likely to be determined through study of salamander tolerance, but are more than likely to include among them suspended solids; biological and chemical oxygen demand; salinity; various heavy metals; various plant nutrients; and various hydrocarbon-based compounds used in pesticides, transportation and industrial applications.

Incorporated in this type of research is analysis of cost-saving mitigation techniques that can serve more than one purpose. For example, development of runoff catchments for hazardous materials could be integrated with lined pond development for recreational fishing in roadside park areas. Similarly, contaminant interception might be diverted to deep filter-beds incorporated into development of parks, gardens, marshes or other low-intensity public use areas to help mitigate costs. Such innovative interception might be considered for urban runoff, wherever it can be demonstrated that such low intensity contaminant filtration will not be more destructive than present techniques or other treatment alternatives.

Airshed-Global

A review of past studies of atmospheric precipitation chemistry is prerequisite to other possible research. Local analysis of wet and dry precipitation may reveal sources of various contaminants if they are identified in the salamander habitats. Watershed sources of contaminants may to some extent be derived from areal sources and would be appropriate input information for watershed models with water quality outputs. Otherwise, monitoring scientific progress about global change and predicted local effects seems appropriate for refining models of population sustainability.

Part D: Ecological and Water Quality Criteria

Only general recommendations can be made at this time for development of ecological and water quality criteria designed to cost-effectively protect salamander viability. Two primary reasons for establishing ecological and water quality criteria are 1) providing standards for monitoring potentially harmful trends and correcting their sources, and 2) preventing harmful events in the first place. The following are basic criteria development recommendations:

1. Criteria should be established to protect only that ecosystem integrity necessary for sustaining population viability.

2. Criteria should be proactive and cost-effective enough to allow sufficient protective monitoring.

3. Instead of reactionary measures of harmful effects, criteria should be sensitive and

predictive indicators of threatening change allowing time for proactive protective action.

4. Criteria should be integrative, if possible, so that relatively few measurements are needed.

5. Criteria should pertain as closely as possible to the primary objective: protecting taxon viability.

6. Criteria should, if possible, broadly serve to protect all taxa in Edwards Aquifer communities, so as to cut monitoring and other cumulative costs.

Development of bench-lines may include two approaches: monitoring habitats that are believed to be most optimal for salamander viability and developing information syntheses in models of optimum conditions. The approaches are interactive. Basic information needed for models also serves to identify sites most likely to serve best as bench-line habitats. Data obtained from habitat monitoring serves to strengthen the models.

Monitoring criteria that seem most useful include sensitive measures of biotic integrity, such as a variation of the index to biotic integrity developed by Karr et al (1991). Even better than the Index to biotic integrity, which depends on some reduction of integrity to signal change, are measures of sublethal behavioral change in more sensitive population members of salamander communities as they react to subtle habitat variation. Although a whole host of water quality parameters could be measured, the cost is high and sometimes not very meaningful unless monitoring is done through short-duration storm events. Such routine monitoring is expensive and each inhabited site may be threatened by a variety of different chemical-physical changes. Once subtle change is indicated by community and behavioral indices, follow-up study seeking cause should start with a search of sources before a blanket analysis is done. The search should be based first on an inventory of all potential threats in the habitats, which should be stored in a database for ready access, addition, synthesis and retrieval. Identification of potential sources will narrow the chemical and biotoxicity analysis needed to apply corrective and preventative action.

Once salamander and community tolerances are defined through research, they need to be compared to existing water quality standards to determine the extent such standards need strengthening for further protection of community integrity and associated salamander viability. Similar analysis is needed of existing watershed development standards to assess the extent that they need strengthening. First, however, certain research is required to better establish connections between watershed process and salamander habitat quantity and quality.

Many problems are associated with reliance on standards, however, especially when catastrophic threats emerge without prior warning. The best approach in this case is to identify the most probable routes through the ecosystems by which catastrophic threats will travel, shunt the threats to some relatively harmless storage site, or warn managers in time for mitigative action at the habitat. Once potentially catastrophic events occur, rapid

communication networks are critical, so that contingincy plans can be acted upon to collect salamanders for temporary holding. Such networks require careful development, possibly requiring research to determine the most "fail-safe" approach.

Part E: Protective Strategies

General Strategies

There exist numerous threats to and protective strategies for sustaining salamander viability. Numerous recent publications address general ecological and management principles for sustaining population viability (Primack 1993). A wide variety of scientific results support the ecosystem paradigm (King 1993) and general conclusions about ecosystem effects, including ecosystem management designed to sustain population and community viability. These generalities provide a foundation for developing more specific management strategies.

Holling (1978) summarized four main points about biological and social properties underlying successful ecological assessment for management purposes: 1) Ecological systems change continuously; even the most static habitats evidence change that may be necessary to sustain ecosystem integrity. 2) Impacts often do not radiate evenly from a causal event, rather events with dramatic effects may originate nearby or far away. Based on what is known in general about ecosystem properties, we cannot conclude that the most threatening events are those that always occur nearest to the organisms of concern. 3) Ecosystems may exhibit several levels of stable behavior. Community composition may shift, for example, causing subsequent shifts and a new and stable distribution of species abundances, which may or may not favor specific taxa of concern. 4) Although there is an organized connection among the parts of ecosystems, everything is not equally important in its connection to everything else. Thus some change may occur in ecosystems without noticeable effect on specific taxa.

These points have specific meaning with respect to the neotenic salamanders of Travis County. The salamanders are adapted to various habitat conditions, possibly including fluctuations in spring discharge quantity and quality. Therefore, strategy directed at reducing habitat variability may be appropriate only to a certain and unknown extent, if at all. Those concerned about the salamander status should not assume that threats to viability are simply and inversely correlated with linear distances from the threat source to the populations. Connectivity between threat sources and populations depends on ecosystem "porosity" and the dimensions of the threats. Careful assessment requires understanding of how both threats and supportive conditions are transmitted through the ecosystem.

For the salamanders, aquifers and watershed characteristics are critically important, but even regional airshed and global phenomena may be critically relevant, given the time scales and the potential sensitivity of the salamanders. Changes may have already established a new order of community stability for at least the Barton Springs Salamander. Past physical changes and subsequent introductions of new species probably created a new community order at the

Barton Springs Pool, which may or may not have enhanced salamander viability. To simply say that the only practical solution to protecting salamander viability is to stop all change in salamander ecosystems is unwarranted unless the changes prove to have harmful consequences. It is apparent though, that salamander ecosystems in Travis County are undergoing dramatic change from natural historic conditions and many of those changes need to be considered in any management plan for salamander viability.

Of the possible conservation means available for protecting viability, the most widely preferred means of assuring population viability is sustaining the support ecosystem's integrity in an optimal state most suited for population reproduction, dispersal and survival (Primack 1993). Many ecosystem processes are not critical for sustaining population viability, however, and ecosystems often undergo extensive cultural modification without threatening populations, especially when cultural change is carefully considered through regional planning. It can be costly finding out which processes are critical and which are irrelevant, however. Where several taxa are linked to similar ecosystems, it may be cheaper to assume that natural ecosystem integrity approaching pristine conditions is best for protecting community viability.

Managers usually favor wild, if culturally modified, ecosystem support for threatened taxa over completely artificial systems because viability of most taxa depends on ecological process that is too poorly understood to sustain artificially. Often subtle attributes and fluctuations are necessary to sustain complete life cycles and population viability and genetic variety. Even when natural historic conditions have been greatly modified by human action, managed ecosystems usually provide more assurance of population and genetic viability than complete dependence on artificial habitats, which are frequently unreliable except for temporary and last-resort maintenance.

Maintenance or recovery of natural habitat is the first avenue for assuring population viability. Maintenance of continuously supportive natural habitat depends on understanding and maintaining critical ecosystem process within limits tolerated by the salamanders. It includes strategies for preventing potentially catastrophic human actions and mitigation of such catastrophes once they have occurred. It includes events sometimes remotely situated in salamander ecosystems as well as events next to or in the occupied habitat. Although sustaining populations in artificial habitat (such as aquarium, zoo or laboratory) and by other artificial means (e.g., cryogenic preservation) are important contingency strategies, they are "last-resort" measures. There is, however, an important place for temporary habitat provision, designed to sustain a population when natural habitat is damaged, and research on artificial habitat, now underway, deserves priority attention.

The perceived threats to the salamanders and their counter-measures exist at several hierarchial levels in the salamander ecosystems: population-taxon level, habitat-community level, aquifer-watershed level, and airshed-biosphere level. Maintenance of population viability requires protection at all hierarchial levels harboring real threats, which include all of those combined natural and cultural events that significantly reduce salamander viability. Each of the hierarchial levels in salamander ecosystems include both natural and cultural interactions

that may act to favor or threaten salamander viability depending on the effectiveness of ecosystem management decisions. With more information, certain perceived threats could recede as other threats grow. Emphasis on different protective strategies are likely to change as decision makers become more informed. Because of that, a certain amount of flexibility is required in developing management strategies.

Strategies also must be comprehensive and long range. Based on concepts of hierarchial interaction, events occurring at higher hierarchial levels often act to constrain ecosystem effects at lower levels (King 1993) and may become the most critical threat to taxon viability. Links within hierarchial levels may be weaker at times than links between hierarchial levels (King 1993). Therefore, regardless of what might be provided in the way of protective measures directly to the population and habitat, impacts from non-habitat environments may ultimately determine the effectiveness of protective measures.

A specific example of this principle can be made from the history suggested at Barton Springs Pool and is the basis for placing catastrophic spills above local habitat disturbance among possible threats by O'Donnell (1994). The best documented impact on Barton Springs Salamanders originated from pool maintenance effects on salamander habitat. The impact, however, did not destroy population viability, possibly because the population was distributed in subterranean habitat beyond reach of the pool cleaning impacts. If true, potentially worse effects would originate from a more pervasive change in the groundwater supplying all of the salamander habitat above and below ground at Barton Springs. Even if past pool maintenance was locally deadly, viability could have been sustained in groundwater refuges if salamanders inhabited those areas. A dramatic change in groundwater quality, in contrast, could have a pervasive effect on all habitat water sources, potentially eliminating the entire population.

Threats and Strategic Countermeasures

Population-Taxon:

Human actions operating directly on the salamander populations can have potentially dramatic impacts. Salamander removal and transfer to other sites, for whatever reason, falls into this category. Removal or transfer effects population loss rate, the reproductive potential and genetic composition. In small populations removal of even a very few animals can have dramatic consequences (Primack 1993). Transfers can result in population hybridization and loss of genetic distinction. For the Travis County taxa, the main concerns stem from recreational use of Barton Springs habitat and research management activity.

The extent to which apparently separate populations in each springhead are in fact interconnected is important in determining basic management strategy. The morphology of the neotenic salamanders in Travis County indicates that subterranean adaptation may best explain past population interchange routes, whether other routes continue to exist. The highly clustered distributions of the three salamander taxa suggest that isolating mechanisms between springhead clusters are extremely effective. Possible refuges and pathways for population

interchange also could be routes of travel for taxon-wide threats created by inappropriate salamander transfer, for example, as well as routes for population recovery in any individual spring head habitat following local extirpation.

The main strategy for mitigating threats to population viability first requires complete definition of taxonomic distinction and distribution and to limit access to population members. All research and recovery efforts involving any threatened individuals need careful assessment of population effect. Until demonstrated otherwise, management should assume that none of the apparently discrete populations are in fact independent. Introductions of genetically distinct but reproductively interactive taxa could result in hybridization. Management also cannot assume that damage to any one springhead population will be recovered by colonization from other springheads, until such recovery mechanisms have been confidently demonstrated. This may be especially true for the Barton Springs Salamander, where only a few closely grouped springheads support the entire population.

Past long-term and intense recreational use of Barton Springs habitat has not extirpated the population and therefore seems compatible with viability objectives. The present strategy of educating the public of salamander presence needs reevaluation for its effectiveness in preventing salamander disturbance and removal by recreationists, however. The present policy of restricting access to Eliza Spring appears wise. In Barton Springs Pool, water depth may be an effective barrier to species access, but salamanders may be vulnerable to swimmers with face masks and scuba equipment. Although education is laudable, it also advertises the vulnerability of the species to those who have little understanding or regard for protection principles. The effectiveness of advertising the presence of scarce species at other sites in Travis County needs careful thought. Anonymity for at least some occupied sites may to be appropriate insurance. Denial of public access to certain key sites may be considered, but could also draw undesirable attention to those populations. Research strategy designed to protect rare species has been discussed in previous sections. A desirable research strategy is to limit destructive research on the threatened taxa by using more abundant test organisms and mathematical models.

Habitat-Community:

Actions operating indirectly on salamanders through their habitat are more likely to be pervasive and completely devastating than threatening to individual population members by poaching or research-management activities. A pervasive threat typically effects most if not all individuals in the habitat. Even though some members of the population may survive a pervasive threat, the number of surviving animals may not be enough to sustain the taxon. Many types of potential habitat change exist where human activities are intense and diverse, as they are in urban environments. These include changes in groundwater discharge, water temperature, water chemistry, suspended sediment, substrate particle size and compaction, habitat morphology (especially relative depths, widths and velocities), associated floral and faunal composition, riparian litter inputs and shade, and surface watershed in the immediate vicinity of the springhead and spring-runs. Changes in both mean parameter value and parameter variation are potentially important. The spatial and temporal variation in

salamander environment that occurred during salamander evolution may be important requirements for sustaining salamander viability. Especially important is the availability of habitat refuges from temporary changes in primary habitat, whatever that may be. Review of population status indicates uncertainty about the extent to which the primary habitat may be subsurface or surface habitat. Very different protection strategy priorities are appropriate, depending on the primacy of habitat.

Changes in community composition often result in altered ecosystem process and a new system stability. Because each population in a community is adapted to both the abiotic habitat and the natural community of other populations in the same habitat, a community functions differently from the simple sum of population parts. Changes in community composition often result in altered ecosystem process and a new system stability. Because each population in a simple community (e.g., one with low diversity) is more likely to play an indispensable role (redundancy of function is less likely), loss or gain of a single population is more likely to have dramatic effects than in more diverse communities. In the salamander communities of Travis County, such change could alter population birth and death rates, changing the probability for population viability. The effects of community change are difficult to predict, perhaps even more so for simple communities where functional redundancy is limited. Sustaining protective ecosystem integrity therefore requires mitigation of existing or possible change in salamander communities if that change ultimately results in the loss of taxon viability. For simple communities, typical of springheads, conservation strategy often promotes the protection or establishment of community integrity that existed under natural historic conditions. However, given the changes that have occurred in salamander ecosystems of Travis County, that may not be the wisest recourse for salamander habitats and communities. One wonders, for example, if the recreational pools built from Barton Springs habitat, might not have affected taxon viability positively, given other cultural changes that have occurred in the salamanders' ecosystems.

Habitats immediately down slope from contaminant sources are exceptionally risky support systems for neotenic salamanders, for example, springheads just down slope from heavy traffic or aging sewerage. Habitats that routinely receive runoff from urban landscapes covered with low-infiltration surfaces typically need more protective attention than habitats receiving runoff from rural watersheds with high material retention and infiltration. However, the specific runoff conditions of each watershed area need to be assessed because of the possible harmful runoff generated by intentional or unintentional human activity. Tactics should include diverting harmful surface runoff and thwarting introductions or removals of community flora and fauna that could threaten salamander viability, including changes in riparian environments. In some cases this will be best done at the source while in other cases, engineered solutions may work best at the habitat. The Barton Creek diversion around Barton Springs, for example, may have had a protective effect on Barton Springs salamanders (although that cannot be conclusively demonstrated). Similar types of structures may be appropriate at certain Jollyville Plateau sites (e.g., piping surface runoff around habitat).

The main habitat-oriented strategy to sustain population viability by protecting or

enhancing the integrity of the habitat system and the community, including surface-flows from immediately adjacent watershed areas into the spring, spring-run and adjacent riparian communities. Until more is known, the most protective strategy assumes existing community taxa are critical for sustaining ecosystem integrity. The most effective way to assure protection is to gain control over habitat access and use, including adjacent terrestrial environment integral to habitat function (e.g., riparian areas and intermittent or perennial tributaries).

Although many springheads now are in public control, they may be the most critical habitats in need of protection. The extent to which remaining sites serving as existing or potential habitat need to be protected depends on how much the site contributes to sustaining population viability. Until the isolating mechanisms for individual sites occupied by salamanders are better understood, the safest assumption for protecting against some pervasive habitat change is to assume that all sites supporting a taxon are part of one intraconnected habitat. Springhead interconnection and position with respect to watersheds and aquifers are important considerations when developing habitat protection strategy. Where threats of groundwater depletion occur, low elevation sites may need the most protection because they are the last refuges from depletion. Where threats of contamination occur, the highest elevation sites may need more protection, if they are above most faults carrying contaminants to spring habitats. An informed strategy requires a ranking of habitat attributes that sum up the pluses and minuses for protecting population viability.

Effective management strategy requires multi-dimensional mapping of all known and potential habitat locations, including the immediate watershed and riparian area and their present and planned land uses. Electronic mapping via Geographic Information Systems is the most useful approach because of its flexibility and the integrative and coordinative functions it provides for planning purposes. Maps should include all nearby impenetrable and otherwise altered surfaces and their drainage connections to the habitats. Use intensities need to be measured and mapped, including traffic rates by category, fuel and sewage flows, and pesticide and fertilizer application rates and other potentially harmful rates. Any planned habitat changes need to be mapped with estimates of land use rates.

Effective management strategy also requires risk analysis. Use of a Geographic Information System will facilitate risk analyses needed to evaluate that habitat protection that will most likely sustain population viability. In the process of doing risk analysis, information gaps and research needs will become clearer. Research needs to be prioritized to assure the greatest cost effectiveness.

Aquifer Threats:

Aquifer systems are the main source of the groundwater that is the mainstay of habitat integrity for the neotenic salamanders in Travis County. Both the quantity stored and the quality of groundwater are determinants of salamander viability. What happens in the aquifer to mitigate or magnify disturbances generated in watersheds contributes to determining the degree of threat faced by the salamanders. Aquifers are conduits for water quantity and quality

changes originating at the watershed surface, but have qualities of their own that modify the effects of surface events on the salamander habitat quantity and quality. The storage (aquifer thickness), transmissivity, filtration, and sorption characteristics of aquifers determine the extent to which an aquifer buffers or accentuates the effects of surface activities on springhead and spring-run habitat.

Aquifer relationships with watersheds are complex and not well understood in specific detail relating to the Travis County salamanders. Remote or widespread changes in groundwater distribution and quality can in concept be caused by distant watershed changes in surface water quality, surface water diversion, ground water pumping, or changes in evapotranspiration and other large landscape features. Groundwater contamination may follow pathways different from those indicated by the surface watershed. Although aquifer changes often have local watershed causes, remote watershed events can have even greater aquifer consequences, depending on aquifer characteristics. Because of long-term lags in groundwater redistribution, threatening changes in aquifer quantity and quality may be in route to spring outlets and virtually unpreventable long before salamander habitat impacts are observed. Certain habitat changes could be so gradual as to defy easy identification until the damage is virtually incontrovertible. Long-term natural change, such as precipitation variation, may have unknown effects on storage of aquifer contaminated water and rates of transmissivity. A complete management strategy requires more research to address these issues.

Even though the threat of groundwater depletion is least immediate among the three outstanding threat categories identified by O'Donnell (1994) for the Barton Springs Salamander, it could become the ultimate constraint on population viability, if groundwater depletions continue as they have. Because Barton Springs are among the lowest-elevation springs in the Edwards Aquifer, they are least likely to dry up. Reliance on other spring flow for various endangered species, such as at San Marcos Spring, decreases the likelihood of groundwater depletion at Barton Springs. The greatest threat at Barton Springs is misjudgment of the groundwater needed to sustain minimal required flow for sustain taxon viability in all of the major springs of the Edwards Aquifer during periods of extreme drought. In the shallower, higher elevation aquifer underlying the Jollyville Plateau, excessive groundwater withdrawal rates are more likely to cause surface habitat to dry up during drought. The extent of harm generated depends on the extent that salamanders can be sustained by subsurface habitats, during what could become worsening drought conditions, which is only generally understood at this time.

Other harmful effects from groundwater depletion could occur as a consequence of more saline groundwater intrusion from adjacent aquifers or because of discharge related effects on reproduction, growth and survival. More subtle interactions between depleted aquifer storage and groundwater contaminants may act against salamander viability as groundwater discharge decreases, even if flow rate otherwise is sufficient for sustaining habitat suitability. Management strategies over a 100-year planning horizon need to consider habitat suitability during the most constraining periods of drought. Because other aquifer segments seem to play a disproportionate role in sustaining habitat during drought, careful attention needs to be paid

to extrapolation of depletion effects to severe drought conditions. This attention should include the role of groundwater depletion in the San Antonio Segment adjacent to the Barton Creek Segment of the aquifer and the Trinity Aquifer underlying the Jollyville Plateau Segment.

The main strategy for aquifer management is to protect or enhance the aquatic aquifer integrity so as to sustain all of its valued uses most beneficially, including sustaining habitats critical for salamander viability. The strategy requires an improved understanding of aquifer distributions, internal flow routes and rates, and connections to the surface. It also requires improved social (educational, legislative, economic) recognition of aquifer attributes and values.

An important aspect of strategic planning is digital "mapping" of existing groundwater amounts and distributions, interconnections with other segments and the surface, and rates of groundwater movement. GIS and other computer-based methods should serve as an organizational framework for all data, which should include measures of precision and accuracy. Such electronic organization will facilitate data integration and ultimately aid development of predictive models that can serve a variety of integrated needs, including salamander protection. Significant water quality variables need mapping, especially those factors salamanders are sensitive to, like salinity and various metallic and organic contaminants. Maps are useful for specifying tactical priorities once the amounts and rates are estimated and resulting risks to salamanders are judged. Because the interconnected aquifer extends widely through the Edwards Plateau, data organization into a GIS is best done at a regional level of political organization with regional or state coordination. The data mapping should be compatible with other information systems designed for strategy development at other ecosystem hierarchial levels, but especially watershed and habitat levels. Appropriate research should be conducted as information needs become clearer.

Watershed Threats:

The salamander population, community, habitat and aquifer functions are constrained by watershed process and its cultural modification. The extent of watershed effects that could occur depends on the extremity of harmful events and the extent that aquifer characteristics modify the impact of potentially harmful watershed events. Water is the most obvious means for short- or long-distance transport of both nourishing and harmful materials to salamander habitats. Although connected environments may not in themselves form habitat, they can profoundly influence habitat suitability as a consequence of water transport from and through the watershed.

Actions occurring in remote and indirectly linked areas of the surface watershed can have remote but catastrophic impacts, mostly by way of the impact on groundwater quality and discharge into spring habitat. An extreme example is the impact that water diversion and aquifer withdrawal by San Antonio, Texas may have during naturally recurring drought periods. Among the most important factors causing concern are the amounts and distribution of impenetrable surface created in the watershed by cultural development and the altered

quality of water draining from altered watershed surface. Other more subtle factors can have additional effects, such as transforming forested watersheds to grass or agricultural uses. Livestock grazing management can be a factor influencing the fraction of flow into ground and surface waters.

The proximity of contaminated surface flows to sinks and subterranean channels leading to the spring habitats is an especially important concern. Diversions of surface flows from or to existing sinks could have critical impact. Catastrophic spills of contaminants into ecosystems connected to salamander habitat are of exceptional concern because 1) transport and use of toxic materials is common in both watersheds, 2) the Edwards Aquifer appears to be especially porous and unfiltered, 3) all springheads supporting an entire salamander population conceivably could be affected by a single spill, and 4) corrective-action response time usually is short.

The primary strategy used to prevent watershed-related threats is to protect or enhance the integrity of the watershed ecosystem, especially focusing on those physical pathways connecting distant points in the watershed most directly to the spring habitats via surface or groundwater routes. Surface water sources, flow rates and sinks need to be electronically mapped in a storage and retrieval system compatible with systems developed for habitats and aquifers. Surface flow origins and flow quality need definition. Data mapping needs to focus on the intermittent and perennial flow routes and contaminant transport routes: especially where water routes cross roads, fuel pipelines, and sewerage lines. Critical information gaps and priority research needs should become clearer in the process of data mapping and preliminary risk analysis. Appropriate research should be conducted to improve management cost-effectiveness as information needs become clearer.

Airshed-Global Threats:

Global effects transmitted through the atmosphere have the least local control, yet could ultimately limit the effectiveness of local strategies in sustaining salamander population viability. The threat from increasing mean annual atmospheric temperatures is an obvious example. Long-distance aerial transport of various contaminants, however, may be the more critical concern if salamanders are especially sensitive to such contaminants. Local areal sources of contaminants are under more local control and their management should be separated from more distant threat sources. Quantitative definition of such airshed-global threats depends on better understanding of global trends and their implications for the viability of the threatened salamander taxa.

The airshed carries various contaminants, including increased loads of hydrogen ions (acidity), various metals, various synthetic compounds, and other toxic materials (Eisenreich 1981). Dust created from tire wear, for example,is a source of local areal contaminants. These may derive from relatively close or quite distant sources depending on emissions height, quantity, and form. The amount of road, roof, parking lot, and other impenetrable surface influences the extent such areal fall-out ends up concentrated in surface flows that ultimately

reach salamander habitats. Areal deposition in watersheds may end up concentrated in surface or groundwater as storm events erode the toxins from the watershed. Effective ecosystem management identifies the relative contribution of these areal sources to water quality changes potentially impacting salamander habitat.

Because of poorly understood interactions among toxins and environmental factors, the total threat to sensitive species may be more than indicated by the simple sum of the component threats. Toxicity, for example, is known to be influenced by both temperature and pH related process, both of which are influenced by global atmospheric process. Certain amphibians, especially frogs, appear to be ultrasensitive to ultraviolet light, which may be increasing in the ambient environment (Moriarty 1988). Although water rapidly absorbs ultraviolet light and cryptic salamander behavior reduces impact, the supportive role of riparian shade may increase in importance.

Local and more global airshed issues need to be differentiated because of the level of responsibility and control that can be assigned to local authorities. Although airshed-global issues are mostly beyond local control, they should not be beyond local concern. Practical strategy includes tracking global trends to gauge potential for background change in salamander habitats. Awareness of global trends provides better insight into the sensitivity of salamanders to change beyond local control and may influence the strategies developed to sustain salamander viability. This information should be useful for analysis of more local policy effectiveness in sustaining salamander viability, especially for long-range policy analysis. Local public interests may be strategically served by joining regional-global networks for information exchange as they become available. Such information ought to be useful for numerous other ecosystem purposes and information gathered locally can contribute to more global applications.

Part F: General Recommendations

General Observations

Ecosystem-based management strategies designed to protect salamander viability should be used following more thorough evaluation of cost effectiveness and practicality. Strategic priorities for ecosystem management need to be identified based on threat sources, locations, probabilities of occurrence, cumulative effects, research unknowns, management practicalities, and relations to similar ecosystem-based issues. Threats fall into immediate and more long-term categories and strategies need to be designed accordingly. The complexity of threat prevention generally increases with increase in the hierarchial level of threat origin. Because solution complexity and time required for problem solving are correlated, management actions need to be partitioned into short-term contingency planning and longer-term strategic planning. Contingency planning needs immediate attention so as to protect salamanders in the interim required to build a more satisfactory ecosystems-based management plan.

Therefore, it is critical to develop a crisis management plan as soon as possible. That

plan should go into effect whenever a catastrophic event threatens taxon viability. This requires an efficient networking system, a well-trained response team, and safe temporary holding habitat for the salamanders. It also requires immediate engineering solutions of obvious existing threat sources, such as spills at L360. Finally it requires careful strategic planning based on existing information and new information gained from research.

An important ecosystems management principle is that ecosystem assessment and management goals for sustaining ecosystem integrity must integrate human culture into the concept of integrated ecosystems, if ecosystems management is to be realistic and effective (Regier 1993). That reality includes the economics of problem solution. Cost control is an important consideration in protecting taxon viability; without it threats to viability may increase through social process. Management decisions need to be made based on social as well as ecological constraints.

Management costs and complexity tend to increase as the hierarchial level for the threat source increases. It is usually cheaper, for example, to protect a population from poaching than to protect the habitat from local contamination, and even more expensive to protect the population from remote watershed sources of contaminants. The costs derive less from ecological complexity than from social complexity, which accumulates at a compound rate as ecosystem hierarchial level increases.

The degree of cost sharing expected from among effected parties will depend in part on the hierarchical level from which ecosystem effects are likely to originate. The more localized the ecosystem function involved and the more specific the issue in question, the more the cost might be expected to be borne by local publics or specific authorities rather than from regional or national publics represented by diverse authorities.

This does not mean local interests ought to be excluded from higher hierarchical concerns, such as large-scale aquifer, watershed, airshed or biosphere changes. Just the opposite is needed. Because higher hierarchical levels in society often constrain local ecosystems management activity, usually through state or federal regulation, local interests are wise to be aware of and contribute to the most informed decision-making at each level. At a practical level, relating to the neotenic taxa in Travis County, it does little good to protect salamander habitat locally if remote management decisions divert necessary groundwater from their habitat or cause harmful atmospheric impacts. Where many different authorities exist more because of political reasons than because of efficient environmental management, the cost of necessary interaction is compounded.

The decision-making process is an integral part of ecosystem dynamics and may become the most limiting factor determining the fate of any ecosystem component. Constraints at each ecosystem hierarchical level can manifest as larger levels of political influence, state and federal regulation, or other social constraint placed on local decision discretion. Strategic management that emphasizes ecosystem integrity must also emphasize coordination across many levels of political influence. Ineffective coordination may be one of the greatest general

threats to sustaining ecosystem integrity and salamander viability.

Government agencies involved with planning and management at each ecosystem hierarchical level need to develop better coordination procedures. The two neotenic salamanders that provide the specific focus of this report are connected to numerous other species through community, watershed, aquifer, atmospheric and other ecosystem dynamics. It is unlikely that local governments operating independently can assure population viability for the numerous species at risk. They need coordination and other services provided by state and Federal agencies with expertise in ecosystems-related processes. Without such coordinated use of management funds, the information and management needs are much less likely to be met for sustaining viability of all threatened taxa.

The number of taxa vulnerable to aquifer-related threats in the Edwards Plateau area is large (Bowles and Arsuffi 1993)and growing (Chippendale et al. 1993b). For each to be cost-effectively protected, including the Travis County salamanders, all need to be treated as part of a larger problem held in common and based in the management of surface and groundwater of the entire Edwards Plateau. The uniqueness of the Edwards Aquifer fauna probably is unparalled in the world (Longley 1989).

A regional strategic plan should be developed and presented to all involved governments with appropriate legal and financial inputs identified for each of the federal, state and local authorities responsible for sustaining salamander viability. A jointly developed Geographical Information System is an excellent start for organizing ecosystems data into an analytical synthesis for the most cost-effective approach to managing rare ecosystems and rare species. Such a data management approach is applicable to and will facilitate analysis integrate across ecosystem hierarchies. This database can facilitate discussion, negotiation, and research and management planning. The alternative approach, taking each species at risk, one by one, with local focus, may ultimately be much more costly and therefore that much more likely to risk loss of population viability.

Conservation organizations are advised to act in concert with a broad ecosystems perspective while addressing each species' fate. This approach will be in compliance with the contemporary ecosystem management understanding of those biological and social system properties underlying successful environmental assessment.

Numerous unique species may be at risk from the cultural depletion of the Edwards Aquifer in all of its various segments and from incremental contamination. Since it would be extremely difficult, if not impossible, to identify areas within the aquifer that are especially critical to protect the unique troglobitic community in the aquifer, an aquifer-wide strategy appears prudent. That strategy should apply, of course, to all surface as well as subterranean organisms affected by changes in aquifer condition.

Conclusions and Summary Comments

Management and related research need immediate prioritization and action. Effective maintenance of salamander taxon viability, the most profound concern, should not be risked by overly prolonged study before protective actions are taken. For that reason the research and management activities need prioritization with focus on the most cost-effective protective strategy. Because cost-effectiveness will prove to be an ultimate determinant of strategic effectiveness, it should not be dismissed as irrelevant. Initial efforts should focus on completion of taxonomic and distribution studies, development of a crisis management protocol including completion of appropriate temporary holding habitat, and careful planning of subsequent ecosystems management activities. Follow up activities include research and management directed at aiding subsequent management decisions, especially with respect to prioritization of habitat protection and management activities.

This review has identified numerous information gaps at most hierarchial levels in salamander ecosystems, which to some extent could impede the goal of protecting salamander viability in Travis County. It has also pointed out that research and management is expensive and that the most cost-effective effort will probable be that which is coordinated with other closely related management problems outside Travis County. Coordinated planning is critical if management and research funds are to be distributed in the most beneficial way toward protecting the unique biological and other attributes of the Edwards Aquifer, including its dependent spring communities.

This coordination should emphasize shared development of database biological and mathematical predictive tools, and indices of ecosystems integrity for analyzing the necessity of various ecosystems management decisions. Regional or state agencies need to take leadership positions in organizing coordinated and shared efforts and results. Costs also need to be shared with emphasis on cost sharing in proportion to benefits.

Planning may be facilitated by regional economic analysis that addresses water values in general and associated biological and taxon viability values in particular. Management of the Edwards Plateau for diverse values including conservation values needs the attention of ecologically oriented economists as well as naturalistic ecologists. The extent to which funds can be diverted specifically to neotenic salamander viability issues is likely to be limited. Development of models, indices, and regional plans should be incorporated with other water and landscape planning whenever specific goals are supportive. Research should be carefully interfaced with specific planning objectives that are organized to cost-effectively serve the needs of scarce and threatened species throughout the region, not just the neotenic salamanders in Travis County.

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