## TREATMENT WETLANDS SECOND EDITION

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ROBERT H. KADLEC SCOTT D. WALLACE



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### Preface

Since the first edition of this book, treatment wetland technology has advanced on all fronts. Considerably more is known today about how treatment wetlands function. Over the last decade, wetland technology has evolved into new reactor configurations, a much broader range of treatment applications, and a dramatically expanded presence worldwide.

This growing knowledge base leads to an increased appreciation of just how complex treatment wetlands are. Because treatment wetlands are strongly influenced by a variety of internal and external ecological cycles, the assumptions that simplify the analysis of conventional reactors in the environmental engineering field can no longer be justified. As wetland technology continues to evolve, much effort is being applied to understand both short-term and long-term variability cycles within treatment wetlands. Because treatment variability strongly influences wetland design, factors that influence performance—especially the role of internal biogeochemical cycles—become paramount in understanding how treatment wetlands function. This knowledge can then be applied to make informed decisions regarding wetland design.

#### WHAT IS A WETLAND?

The meaning of the word *wetland* has been severely stretched in the treatment wetland literature. We would generally insist that wetlands have plants, water, and some kind of media. Without plants they are soil, sand, or gravel filters, or ponds. In fact, planted gravel filters— meaning all subsurface flow wetlands—have no natural wetland analog. Similarly, it is not unusual to hear discussion of "treatment wetlands" that do not have plants. We have tried to use commonly accepted terminology for systems that are generally regarded as within the scope of the treatment wetland field. We have also distinguished systems based on their hydrology, which may be horizontal flow, pulse-feed vertical, fill-and-drain, or recirculating.

#### SCALING FACTORS

Treatment wetlands are in-the-ground, outdoor systems. With other visions guiding them, treatment wetland researchers sometimes find wetlands to be potted plants, pots filled with gravel and no plants, sections of pipe, flasks, test tubes, and all manner of tubs, tanks, and troughs, sometimes with recently inserted propagules. Indoor systems do not experience wind, sun, birds, and animals. When the size is too small, the system is subject to severe edge effects. Although comparative results from small lab systems are useful, there is often the unstated assumption that they would represent the treatment performance of a full-scale wetland. We have tried to be reasonably careful by drawing attention to scale with the terms *microcosm*, *mesocosm*, and *pilot project*.

#### SHORT-TERM STUDIES

We find too many studies are based on infant or juvenile ecosystems, which have not had time to mature into the full suite of components that occur in fully developed wetlands. We also find too many studies focus on short-term events. This, we believe, is like interpreting the meal-time hamburger intake rate of teenage boys and girls as their sustainable caloric intake.

For instance, the development of bed clogging in HSSF wetlands has not been studied in a systematic way in the academic community. Recent knowledge of bed clogging has come from the hydraulic failure of full-scale systems (often at a high price) because clogging phenomena takes longer to develop than the tenure of a typical graduate student. As a result, the long-term viability, and maintenance requirements, of HSSF wetlands is still unknown, despite the fact that thousands of systems have been constructed worldwide.

It is fortunate that there are now numerous full-scale projects to balance the data scales.

#### WHAT'S NEW?

Of course, there is much more information available now than in 1995 when the previous analyses were completed. The doubling time of the available data is on the order of two or three years, because old systems continue to return new information as more and more systems come on line in more and more application areas. As a consequence, about 90% of the data used in support of this book was not available at the time of the first edition. It has been reassuring to find that most of the data and interpretations of the first edition have stood up well to the test of time, but not surprising to find that some numerical interpretation had to be updated.

Data analysis in the first edition was predicated on the plug flow assumption, despite the known fact that virtually no treatment wetland actually tested out as plug flow. It is now understood that while this may provide acceptable interpolation on existing performance ranges, it can lead to very bad extrapolations that should not be used in design. Further, it has been recognized that weathering of the mixtures that comprise many of the standard wastewater parameters will also invalidate the plug flow assumption. Accordingly, a mixing parameter has been added to the mathematical representation of wetland behavior.

#### **DESIGN TOOLS**

With the advent and proliferation of desktop computing, expectations for calculational detail have risen markedly in the last 15 years. It is no longer necessary to be given a single equation, arranged to be solved for the single variable of interest. This second edition is predicated on the extensive use of spreadsheets, and the large array of iterative and optimization tools that go with them. The scientific design team for a constructed wetland must include that capability, or else be constrained to simple scale-up or scale-down for a repetitive design.

In the first edition, central tendency rate coefficients were presented, along with tables detailing the values for individual systems. Several investigators soon found that their results did not match the central tendencies, and incorrectly concluded that something must be wrong. In this edition, we have therefore opted to present the distributions of rate coefficients across numerous wetlands of all types, so that new results may be placed in that spectrum, and designs may be selected with different positions across the intersystem landscape.

The scatter of wetland outlet concentrations around an often-seasonal trend is another type of variability to be accounted. The first edition utilized maximum monthly deviations across the year. Here, the annual pattern is accounted separately, based on system performances, and various percentiles of the exceedance distribution are presented as a necessary part of design.

Among the differences between the new and the old data interpretations, the narrowing of the gaps between surface and subsurface flow system performance and cost are perhaps the most intriguing. Based on new and greatly expanded data analysis, subsurface flow wetlands do not enjoy much of a performance margin on a per unit area basis, and may be less effective than surface flow systems for some contaminants. However, the cost differential is much less than previously thought, when comparable-sized wetlands are evaluated, but still remains about a three to one capital advantage for surface flow. Therefore, nuisance and health hazard avoidance rules the selection of wetland type.

#### **TECHNOLOGY SELECTION**

In the early years of constructed wetland technology, and to some extent continuing today, there was a tendency to consider wetlands as stand-alone devices, usually accompanied by pretreatment. It is now understood that series and parallel natural system networks, perhaps involving recirculation, are sometimes better choices. Combinations of vertical flow, horizontal subsurface flow, ponds, and free water surface wetlands are increasingly being used.

#### THIS BOOK

This book has been updated to reflect the dramatic advances in wetland technology over the last 12 years. The authors of this second edition come from different backgrounds, and work in different aspects of the treatment wetland field. By combining our knowledge and experience, we have endeavored to present a broad range of information regarding the science, hydrology, hydraulics, reactor theory, applied design, implementation, cost, and O&M of treatment wetland systems.

The format of the second edition reflects a dual approach. Part I is organized in a manner that allows the reader to explore the internal mechanisms by which treatment wetlands operate. Existing projects and operating results from real-world treatment wetlands are utilized extensively. Internal mechanisms, their influence on treatment performance, and their effect on system variability are explored in detail in Part I.

Part II is organized to allow the reader to examine how performance data is analyzed and applied to the design process. Like the first edition, this book adopts a performancebased approach to design, in addition to presenting design tools such as loading charts and scaling factors. Continuing with the theme of practical implementation, Part II also summarizes current knowledge that is key to getting wetland projects built, including construction methods, cost information, and operation & maintenance (O&M) requirements.

We have not repeated the natural wetland fundamentals that are contained in the first edition, nor have we reiterated databases or case histories contained therein. All other topics have been nearly totally rewritten, as required by the vastly increased data sources and understanding that have developed in the many years since the first edition.

However, as much as things have changed, some things remain the same. The predictions made in the first edition about rapid evolution of treatment wetlands have certainly proven true. We expect that, if anything, this rate of change will continue to increase after the publication of this second edition, which might have been more properly called *Treatment Wetlands II*.

> Robert H. Kadlec Scott D. Wallace

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> Robert H. Kadlec Scott D. Wallace

### Authors

**Robert H. Kadlec** holds B.S., M.S., and Ph.D. degrees in chemical engineering from the University of Wisconsin and University of Michigan, 1958–1962. That era saw the culmination of the "unit operations" approach to chemical processing, and the transition to the use of principles of transport phenomena to describe transfer and reaction rates in a wide variety of chemical and biochemical processes. Those techniques and analytical tools are also the foundation of today's environmental engineering. Bob began applying engineering analysis to wetland processes in 1970, with the goal of managing wetlands for water quality improvement. The result was the Houghton Lake natural wetland treatment system, which is still operating successfully.

Research on that natural wetland, and on the ensuing 30 years of its operation for engineered treatment, formed the early framework for Dr. Kadlec's development of wetland process characterization. The technology has grown tremendously, and so has Bob's involvement in treatment wetland projects. He has participated in over 250 projects, ranging from simple feasibility studies to comprehensive university research projects. Early university studies focused primarily on wetland hydrology and water chemistry. In the course of many projects, a good deal of knowledge of practical ecology was imparted by his colleagues.

He has worked on treatment wetlands in many states and several other countries, participating in the design of over a hundred treatment wetlands. Major and long-running projects have included Houghton Lake, Michigan; Incline Village, Nevada; Hillsdale, Michigan; Columbia, Missouri; and the Everglades Stormwater Treatment Areas. He is past chairman of the International Water Association (IWA) Specialist Group on the Use of Macrophytes in Water Pollution Control. He has authored or coauthored over 130 publications on treatment wetlands, in addition to dozens of project reports. He was a proposer and developer of the U.S. EPA North American Treatment Wetland Database.

Dr. Kadlec retired from his teaching duties in 1993, and is currently doing business as Wetland Management Services,

providing specialty consulting services to a wide range of governmental and private organizations. His contributions to this book are an effort to consolidate over three decades of research and practical experience.

**Scott D. Wallace** began his career as a wastewater treatment plant operator, and also worked as a field technician and analytical chemist. He earned a B.S. in civil engineering (1986) and an M.S. in environmental engineering (1989), both from the University of Iowa. Scott has worked full-time as a consulting engineer since 1988, and has been employed at CH2M HILL, Shive-Hattery Engineers and Architects, and HDR Engineering. Scott began designing treatment wetlands in 1992, beginning with the Indian Creek Nature Center, one of the first cold-climate subsurface flow wetlands in the United States.

In 1997, he cofounded North American Wetland Engineering (NAWE), a consulting firm focused on the development and application of treatment wetlands. Since then, he has designed over 200 treatment systems, the majority of which involve wetlands. NAWE was acquired by Jacques Whitford in 2007, and Scott currently works as a principal in the Water Resources Sector for Jacques Whitford. He consults on a wide variety of projects in the United States and internationally.

Scott has been active in research and development, and holds 5 patents on wastewater treatment systems, including aerated subsurface flow wetlands, a technology briefly discussed in this book. He is a registered professional engineer in 22 states, and has written numerous technical papers on treatment wetlands. Scott was the principal investigator for *Small-Scale Constructed Wetland Treatment Systems; Feasibility, Design Criteria, and O&M Requirements,* a design manual published by the Water Environment Research Foundation (WERF) in 2006. He is an active member of the IWA Specialist Group on the Use of Macrophytes in Water Pollution Control.

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# Appendix A: Lists of Basis Wetlands

This book is based on the analysis of data from many wetlands, and the associated experiences of cost and implementation. The appendix summarizes those wetland cells and systems that have contributed to this basis of analysis, by name and country (and by state when appropriate). Tables in the various chapters provide extensive referencing, dictated by availability of publications. In some instances, we have relied upon project reports and our own data compilations of published and unpublished results.

It is certain that differences in sampling and laboratory protocols have contributed significantly to the data scatter for wetland performance parameters. There is no simple way to evaluate data quality from the various wetlands, and any attempt to screen the data would be highly suspect in and of itself, as it would be a reflection of the bias of the reviewer. The periods of record vary, with some systems possessing many years of information. In general, very short periods of record, i.e., days or weeks, have been excluded. Laboratory microcosm studies are not included here because conditions are generally too far removed from field environments. We concluded early in the process of information analysis that there are no single "definitive" studies that are superior to others, despite the hopes of individual investigators. In fact, focusing on one study leads to the loss of understanding of intersystem variability and the full loading spectrum that has been explored by the greater number of wetlands.

The lists given here are intended to assist the reader in regionalizing a search for further information relevant to treatment wetlands in a particular climatic zone. However, the lists are not geographically balanced because treatment wetland technology is not geographically uniform, and data are not always accessible despite large numbers of systems in a given region.

The three main types of treatment wetlands are considered separately. Of the total of 950 basis wetlands, 488 are FWS, 362 are HSSF, and 100 are VF. It is understood that these proportions are not indicative of the entire universe of operating systems, but it is believed that the sample sizes are sufficient to characterize the three variants of the technology.

The systems listed in Tables A.1, A.2, and A.3 provided data that were utilized to determine *k*-rates, temperature coefficients, or background concentrations. This is by no means a definitive listing of treatment wetlands, but does provide the reader an indication of systems with significant monitoring data.

| FWS System Name | Identifier   | State/Province     | Country   |
|-----------------|--------------|--------------------|-----------|
| Bahco           |              |                    | Argentina |
| San Tomé        |              |                    | Argentina |
| Blacktown       |              | New South Wales    | Australia |
| Bue Mountain    |              | New South Wales    | Australia |
| Byron Bay       | WB2-3        | New South Wales    | Australia |
| Byron Bay       | WB3-4        | New South Wales    | Australia |
| Byron Bay       | WB4-5        | New South Wales    | Australia |
| Byron Bay       | WB5-6        | New South Wales    | Australia |
| Byron Bay       | WB6-7        | New South Wales    | Australia |
| Richmond        | Open         | New South Wales    | Australia |
| Richmond        | Myriophyllum | New South Wales    | Australia |
| Tom's Gully     |              | Northern Territory | Australia |
| Woodcutters     |              | Northern Territory | Australia |
| Calamvale       |              | Queensland         | Australia |
| Coorparoo       |              | Queensland         | Australia |
| Piricicaba      |              |                    | Brazil    |
| Vancouver       | P15.1        | British Columbia   | Canada    |
| Vancouver       | P15.2        | British Columbia   | Canada    |
| Vancouver       | P30.1        | British Columbia   | Canada    |
| Vancouver       | P30.2        | British Columbia   | Canada    |
| Vancouver       | UP30.1       | British Columbia   | Canada    |
| Vancouver       | UP30.2       | British Columbia   | Canada    |
| Oak Hammock     |              | Manitoba           | Canada    |

#### TABLE A.1 Free Water Surface Wetlands

(Continued)

| FWS System Name          | Identifier  | State/Province        | Country |
|--------------------------|-------------|-----------------------|---------|
| Roblin                   |             | Manitoba              | Canada  |
| Simplot                  | Brandon     | Manitoba              | Canada  |
| Hay River                |             | Northwest Territories | Canada  |
| Hebert                   |             | Nova Scotia           | Canada  |
| Brighton                 |             | Ontario               | Canada  |
| Cobalt                   |             | Ontario               | Canada  |
| Elliot Lake              | Elliot Lake | Ontario               | Canada  |
| Essex County             |             | Ontario               | Canada  |
| Falconbridge             |             | Ontario               | Canada  |
| Gloucester               |             | Ontario               | Canada  |
| Kanata                   | Kanata      | Ontario               | Canada  |
| Kitchener                |             | Ontario               | Canada  |
| Lambton                  |             | Ontario               | Canada  |
| Listowel                 | 1           | Ontario               | Canada  |
| Listowel                 | 2           | Ontario               | Canada  |
| Listowel                 | 3           | Ontario               | Canada  |
| Listowel                 | 4           | Ontario               | Canada  |
| Listowel                 | 5           | Ontario               | Canada  |
| Musselwhite              |             | Ontario               | Canada  |
| Perth County             |             | Ontario               | Canada  |
| Region of Ottawa–Carlton |             | Ontario               | Canada  |
| Riverwalk                |             | Ontario               | Canada  |
| Arvida                   |             | Quebec                | Canada  |
| Fontanges                |             | Quebec                | Canada  |
| Estevan                  |             | Saskatchewan          | Canada  |
| Humboldt                 |             | Saskatchewan          | Canada  |
| Guangdong                |             |                       | China   |
| Alastaro                 |             |                       | Finland |
| Flytträsk                |             |                       | Finland |
| Hovi                     |             |                       | Finland |
| Kis-Balaton              |             |                       | Hungary |
| Warangal                 |             |                       | India   |
| County Galway            | Bed 1       |                       | Ireland |
| County Galway            | Bed 2       |                       | Ireland |
| Johnstown Castle         |             |                       | Ireland |
| Kilmeadan                |             |                       | Ireland |
| Rathermon                |             |                       | Ireland |
| Waterford                | Anne Valley |                       | Ireland |
| Cecchi                   |             |                       | Italy   |
| Chiampo Valley           |             |                       | Italy   |
| La Croce                 |             |                       | Italy   |
| Ornellaia                |             |                       | Italy   |
| Harutori                 | 1           |                       | Japan   |
| Harutori                 | 2           |                       | Japan   |
| Harutori                 | 3           |                       | Japan   |
| Kahokugata               |             |                       | Japan   |
| Kojima                   | 1           |                       | Japan   |
| Kojima                   | 2           |                       | Japan   |
| Mizomoto                 |             |                       | Japan   |
| Nagano                   | 1           |                       | Japan   |
| Nagano                   | 2           |                       | Japan   |
| Nagano                   | 3           |                       | Japan   |
| Nagano                   | 4           |                       | Japan   |
| Sanno                    | 1           |                       | Japan   |

| FWS System Name     | Identifier | State/Province | Country      |
|---------------------|------------|----------------|--------------|
| Sanno               | 2          |                | Japan        |
| Sanno               | 3          |                | Japan        |
| Sanno               | 4          |                | Japan        |
| Sanno PWRI          | 1          |                | Japan        |
| Sanno PWRI          | 2          |                | Japan        |
| Sanno PWRI          | 3          |                | Japan        |
| Sanno PWRI          | 4          |                | Japan        |
| Sanno PWRI          | 5          |                | Japan        |
| Sanno River         | River      |                | Japan        |
| Seimei              |            |                | Japan        |
| Watarase            |            |                | Japan        |
| Yasato-machi        |            |                | Japan        |
| Marrakech           |            |                | Morrocco     |
| Texel               | 1          |                | Netherlands  |
| Texel               | 2          |                | Netherlands  |
| Texel               | 3          |                | Netherlands  |
| Texel               | 4          |                | Netherlands  |
| Texel               | 5          |                | Netherlands  |
| Texel               | 6          |                | Netherlands  |
| Texel               | 7          |                | Netherlands  |
| Texel               | 8          |                | Netherlands  |
| Beachlands/Maraetai |            |                | New Zealand  |
| Blenheim            |            |                | New Zealand  |
| Christchurch        |            |                | New Zealand  |
| Hautoriu            |            |                | New Zealand  |
| Hikumutu WWTP       |            |                | New Zealand  |
| Horotiu             |            |                | New Zealand  |
| Kohukohu            |            |                | New Zealand  |
| Opunake             |            |                | New Zealand  |
| Portland            |            |                | New Zealand  |
| Pukekohe            |            |                | New Zealand  |
| Rangiuru            |            |                | New Zealand  |
| Taumaranui          |            |                | New Zealand  |
| Titoki              |            |                | New Zealand  |
| Toenepi             |            |                | New Zealand  |
| Wellsford           |            |                | New Zealand  |
| Whangarei           |            |                | New Zealand  |
| Bolstad             |            |                | Norway       |
| Braskerud           | А          |                | Norway       |
| Braskerud           | С          |                | Norway       |
| Braskerud           | F          |                | Norway       |
| Braskerud           | G1         |                | Norway       |
| Braskerud           | G2         |                | Norway       |
| Esval               |            |                | Norway       |
| Orcopampa           |            |                | Peru         |
| Tucush              |            |                | Peru         |
| Frambork            |            |                | Poland       |
| Motorway            |            |                | Slovenia     |
| Mpophomeni          |            |                | South Africa |
| Esklistuna          | Ekeby      |                | Sweden       |
| Hassleholm          | Magle      |                | Sweden       |
| Isgrannatorp        | <b>0</b>   |                | Sweden       |
| Linkoping           |            |                | Sweden       |
| <u>.</u>            |            |                | (Continued)  |

| FWS System Name  | Identifier | State/Province | Country        |
|------------------|------------|----------------|----------------|
| Oxelösund        |            |                | Sweden         |
| Snogeröd         |            |                | Sweden         |
| Vomb East        |            |                | Sweden         |
| Vomb West        |            |                | Sweden         |
| Kaohsiung        |            |                | Taiwan         |
| Airton           |            |                | United Kingdom |
| Bishop Wilton    |            |                | United Kingdom |
| Brentwood        |            |                | United Kingdom |
| Carperby         |            |                | United Kingdom |
| Cherry Burton    |            |                | United Kingdom |
| Crow Edge        |            |                | United Kingdom |
| Dagenham         |            |                | United Kingdom |
| Meltham          |            |                | United Kingdom |
| Northumberland   | Shilbottle |                | United Kingdom |
| Slingsby         |            |                | United Kingdom |
| Stockley         | Bed 1      |                | United Kingdom |
| Stockley         | Bed 2      |                | United Kingdom |
| Stockley         | Bed 3      |                | United Kingdom |
| Tupton           |            |                | United Kingdom |
| Wentworth Castle | Bed 1      |                | United Kingdom |
| Wentworth Castle | Bed 2      |                | United Kingdom |
| Wentworth Castle | Bed 3      |                | United Kingdom |
| Wentworth Castle | Bed 4      |                | United Kingdom |
| Wetwang          | Bed 1      |                | United Kingdom |
| Wetwang          | Bed 2      |                | United Kingdom |
| Wetwang          | Bed 3      |                | United Kingdom |
| Wheal Jane       |            |                | United Kingdom |
| Auburn Poultry   | 1          | Alabama        | United States  |
| Auburn Poultry   | 2          | Alabama        | United States  |
| Auburn Poultry   | 3          | Alabama        | United States  |
| Fort Deposit     | T:1–2      | Alabama        | United States  |
| Hurtsboro        | 1          | Alabama        | United States  |
| Hurtsboro        | 2          | Alabama        | United States  |
| Muscle Shoals    |            | Alabama        | United States  |
| Sand Mountain    | 1          | Alabama        | United States  |
| Sand Mountain    | 2          | Alabama        | United States  |
| Sand Mountain    | 3          | Alabama        | United States  |
| Sand Mountain    | 4          | Alabama        | United States  |
| Sand Mountain    | 5          | Alabama        | United States  |
| Widows Creek     |            | Alabama        | United States  |
| Anchorage        |            | Alaska         | United States  |
| Fairbanks        |            | Alaska         | United States  |
| Kingman          |            | Arizona        | United States  |
| Show Low         |            | Arizona        | United States  |
| Tres Rios        | C1         | Arizona        | United States  |
| Tres Rios        | C2         | Arizona        | United States  |
| Tres Rios        | H1         | Arizona        | United States  |
| Tres Rios        | H2         | Arizona        | United States  |
| Tres Rios        | R1         | Arizona        | United States  |
| Tres Rios        | R2         | Arizona        | United States  |
| Tres Rios        | R3         | Arizona        | United States  |
| Tres Rios        | R4         | Arizona        | United States  |
| Tres Rios        | R5         | Arizona        | United States  |
| Tres Rios        | R6         | Arizona        | United States  |

| FWS System Name                 | Identifier | State/Province | Country       |
|---------------------------------|------------|----------------|---------------|
| Tres Rios                       | R7         | Arizona        | United States |
| Tres Rios                       | R8         | Arizona        | United States |
| Tres Rios                       | R9         | Arizona        | United States |
| Tres Rios                       | R10        | Arizona        | United States |
| Tres Rios                       | R11        | Arizona        | United States |
| Tres Rios                       | R12        | Arizona        | United States |
| Tucson                          | Sweetwater | Arizona        | United States |
| Arcata Enhancement              | Gearheart  | California     | United States |
| Arcata Enhancement              | Allen      | California     | United States |
| Arcata Enhancement              | Hauser     | California     | United States |
| Arcata Treatment                |            | California     | United States |
| Brawley                         |            | California     | United States |
| Corcoran                        |            | California     | United States |
| DUST                            |            | California     | United States |
| Gustine                         | 1A         | California     | United States |
| Gustine                         | 1B         | California     | United States |
| Gustine                         | 1C         | California     | United States |
| Gustine                         | 1D         | California     | United States |
| Gustine                         | 2A         | California     | United States |
| Gustine                         | 2B         | California     | United States |
| Gustine                         | 6D         | California     | United States |
| Hayward                         |            | California     | United States |
| Hemet                           |            | California     | United States |
| Imperial                        |            | California     | United States |
| Irvine Ranch                    |            | California     | United States |
| Lake Tahoe                      |            | California     | United States |
| Mountain View Sanitary District |            | California     | United States |
| Oxnard                          |            | California     | United States |
| Prado                           |            | California     | United States |
| Richmond                        |            | California     | United States |
| Sacramento                      | 1          | California     | United States |
| Sacramento                      | 2          | California     | United States |
| Sacramento                      | 3          | California     | United States |
| Sacramento                      | 4          | California     | United States |
| Sacramento                      | 6 A & B    | California     | United States |
| Sacramento                      | 7          | California     | United States |
| Sacramento                      | 8          | California     | United States |
| Sacramento                      | 9          | California     | United States |
| Sacramento                      | 10         | California     | United States |
| San Diego                       |            | California     | United States |
| Santa Rosa                      | Kelly Farm | California     | United States |
| Avondale                        |            | Colorado       | United States |
| Bennett                         |            | Colorado       | United States |
| Crowley                         |            | Colorado       | United States |
| Crowley Correctional Facility   |            | Colorado       | United States |
| Delta                           |            | Colorado       | United States |
| Dove Creek                      |            | Colorado       | United States |
| La Veta                         |            | Colorado       | United States |
| Manzanola                       |            | Colorado       | United States |
| Ouray                           |            | Colorado       | United States |
| Platteville                     |            | Colorado       | United States |
| Shop Creek                      |            | Colorado       | United States |
| Silt                            |            | Colorado       | United States |
|                                 |            |                | (Continued)   |

| FWS System Name                     | Identifier | State/Province | Country       |
|-------------------------------------|------------|----------------|---------------|
| University of Connecticut           | T: 1–3     | Connecticut    | United States |
| Apalachicola                        |            | Florida        | United States |
| Apopka                              |            | Florida        | United States |
| Boney Marsh                         |            | Florida        | United States |
| Boot                                |            | Florida        | United States |
| Champion                            | А          | Florida        | United States |
| Champion                            | В          | Florida        | United States |
| Champion                            | С          | Florida        | United States |
| Champion                            | D          | Florida        | United States |
| Champion                            | Е          | Florida        | United States |
| Champion                            | F          | Florida        | United States |
| Clermont                            | Plot H     | Florida        | United States |
| Deer Park                           | 1A         | Florida        | United States |
| Escambia County                     |            | Florida        | United States |
| Everglades Full Scale               | STA2       | Florida        | United States |
| Everglades Full Scale               | STA1E      | Florida        | United States |
| Everglades Full Scale               | STA1W      | Florida        | United States |
| Everglades Full Scale               | STA3/4     | Florida        | United States |
| Everglades Full Scale               | STA 5      | Florida        | United States |
| Everglades Full Scale               | STA6       | Florida        | United States |
| Everglades Nutrient Removal Project | ENRP       | Florida        | United States |
| Everglades Nutrient Removal Project | STC1       | Florida        | United States |
| Everglades Nutrient Removal Project | STC2       | Florida        | United States |
| Everglades Nutrient Removal Project | STC3       | Florida        | United States |
| Everglades Nutrient Removal Project | STC4       | Florida        | United States |
| Everglades Nutrient Removal Project | STC5       | Florida        | United States |
| Everglades Nutrient Removal Project | STC6       | Florida        | United States |
| Everglades Nutrient Removal Project | STC7       | Florida        | United States |
| Everglades Nutrient Removal Project | STC8       | Florida        | United States |
| Everglades Nutrient Removal Project | STC9       | Florida        | United States |
| Everglades Nutrient Removal Project | STC10      | Florida        | United States |
| Everglades Nutrient Removal Project | STC11      | Florida        | United States |
| Everglades Nutrient Removal Project | STC12      | Florida        | United States |
| Everglades Nutrient Removal Project | STC13      | Florida        | United States |
| Everglades Nutrient Removal Project | STC14      | Florida        | United States |
| Everglades Nutrient Removal Project | STC15      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC1       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC2       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC3       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC4       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC5       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC6       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC7       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC8       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC9       | Florida        | United States |
| Everglades Nutrient Removal Project | NTC10      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC11      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC12      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC13      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC14      | Florida        | United States |
| Everglades Nutrient Removal Project | NTC15      | Florida        | United States |
| Everglades Periphyton               | F1         | Florida        | United States |
| Everglades Periphyton               | F2         | Florida        | United States |
| Everglades Periphyton               | F3         | Florida        | United States |

| FWS System Name                    | Identifier | State/Province | Country       |
|------------------------------------|------------|----------------|---------------|
| Everglades Periphyton              | F4         | Florida        | United States |
| Gainesville                        |            | Florida        | United States |
| Greenwood                          |            | Florida        | United States |
| Hidden River                       |            | Florida        | United States |
| Lakeland                           | 1          | Florida        | United States |
| Lakeland                           | 2          | Florida        | United States |
| Lakeland                           | 3          | Florida        | United States |
| Lakeland                           | 4          | Florida        | United States |
| Lakeland                           | 5          | Florida        | United States |
| Lakeland                           | 6          | Florida        | United States |
| Lakeland                           | 7          | Florida        | United States |
| Orange County Eastern Service Area | 1          | Florida        | United States |
| Orange County Eastern Service Area | 2          | Florida        | United States |
| Orlando Easterly                   | Stratum 1  | Florida        | United States |
| Orlando Easterly                   | Stratum 2  | Florida        | United States |
| Orlando Easterly                   | Stratum 3  | Florida        | United States |
| Orlando Easterly                   | Stratum 4  | Florida        | United States |
| Orlando Easterly Wetland           | Stratum 1  | Florida        | United States |
| Orlando Easterly Wetland           | Stratum 2  | Florida        | United States |
| Orlando Easterly Wetland           | Stratum 3  | Florida        | United States |
| Orlando Easterly Wetland           | Stratum 4  | Florida        | United States |
| Palm Beach County                  |            | Florida        | United States |
| Poinciana                          | T:1        | Florida        | United States |
| Reedy Creek OFWTS                  | 2          | Florida        | United States |
| Reedy Creek WTS1                   | 1          | Florida        | United States |
| Sanford                            |            | Florida        | United States |
| Silver Springs Shores              | Lake Coral | Florida        | United States |
| Tampa Office                       |            | Florida        | United States |
| Titusville                         |            | Florida        | United States |
| Waldo                              |            | Florida        | United States |
| Augusta                            |            | Georgia        | United States |
| Clayton County                     |            | Georgia        | United States |
| McMichael Dairy                    |            | Georgia        | United States |
| Cataldo                            |            | Idaho          | United States |
| Idaho Springs                      | Cell A     | Idaho          | United States |
| Des Plaines                        | 3          | Illinois       | United States |
| Des Plaines                        | 4          | Illinois       | United States |
| Des Plaines                        | 5          | Illinois       | United States |
| Des Plaines                        | 6          | Illinois       | United States |
| Embarrass River                    | А          | Illinois       | United States |
| Embarrass River                    | В          | Illinois       | United States |
| Embarrass River                    | D          | Illinois       | United States |
| Norwood Farms                      |            | Indiana        | United States |
| Purdue University                  | A1         | Indiana        | United States |
| Purdue University                  | A2         | Indiana        | United States |
| Purdue University                  | A3         | Indiana        | United States |
| Purdue University                  | A4         | Indiana        | United States |
| Purdue University                  | B1         | Indiana        | United States |
| Purdue University                  | B2         | Indiana        | United States |
| Purdue University                  | B3         | Indiana        | United States |
| Purdue University                  | B4         | Indiana        | United States |
| Purdue University                  | C1         | Indiana        | United States |
| Purdue University                  | C2         | Indiana        | United States |

| FWS System Name            | Identifier  | State/Province | Country       |
|----------------------------|-------------|----------------|---------------|
| Purdue University          | C3          | Indiana        | United States |
| Purdue University          | C4          | Indiana        | United States |
| Purdue University          | D1          | Indiana        | United States |
| Purdue University          | D3          | Indiana        | United States |
| Purdue University          | D4          | Indiana        | United States |
| Tom Brothers Farm          |             | Indiana        | United States |
| Army Ammunition Plant      |             | Iowa           | United States |
| Brenton Cattle             |             | Iowa           | United States |
| Norwalk                    |             | Iowa           | United States |
| Norwalk                    |             | Iowa           | United States |
| Benton                     | 1 Cattail   | Kentucky       | United States |
| Benton                     | 2 Woolgrass | Kentucky       | United States |
| Crittenden County          | •           | Kentucky       | United States |
| Mercer County              |             | Kentucky       | United States |
| Pembroke                   |             | Kentucky       | United States |
| Russelville                |             | Kentucky       | United States |
| Union County               |             | Kentucky       | United States |
| Norco                      |             | Louisiana      | United States |
| Saint Louis University     | 1           | Louisiana      | United States |
| Saint Louis University     | 2           | Louisiana      | United States |
| Saint Louis University     | 3           | Louisiana      | United States |
| University of SW Louisiana | 1           | Louisiana      | United States |
| University of SW Louisiana | 2           | Louisiana      | United States |
| University of SW Louisiana | 3           | Louisiana      | United States |
| Braun                      | Braun       | Maryland       | United States |
| Eastern Shore              | B1          | Maryland       | United States |
| Eastern Shore              | B2          | Maryland       | United States |
| Foster                     | Foster      | Maryland       | United States |
| Mays Chapel                |             | Maryland       | United States |
| Queen Anne                 |             | Maryland       | United States |
| Great Meadows              |             | Massachusetts  | United States |
| Ann Arbor                  |             | Michigan       | United States |
| Bellaire                   |             | Michigan       | United States |
| Commerce Township          |             | Michigan       | United States |
| Houghton Lake              | 1           | Michigan       | United States |
| Houghton Lake              | 2           | Michigan       | United States |
| Kinross (Kincheloe)        | 1           | Michigan       | United States |
| Lansing                    |             | Michigan       | United States |
| Lapeer                     |             | Michigan       | United States |
| Onaway                     |             | Michigan       | United States |
| Vermontville               |             | Michigan       | United States |
| Biwabik                    |             | Minnesota      | United States |
| Clear Lake                 |             | Minnestoa      | United States |
| Dunka Mine                 |             | Minnestoa      | United States |
| Isanti-Chisago             |             | Minnestoa      | United States |
| Lake McCarrons             |             | Minnestoa      | United States |
| Spring Lake                |             | Minnestoa      | United States |
| Hernando                   | 1           | Mississippi    | United States |
| Hernando                   | 2           | Mississippi    | United States |
| Hernando                   | 3           | Mississippi    | United States |
| Hernando                   | 4           | Mississippi    | United States |
| Leaf River                 | Pond 1      | Mississippi    | United States |
| Leaf River                 | Pond 2      | Mississippi    | United States |
| Leaf River                 | Pond 3      | Mississippi    | United States |

| Newton1MississippiUnitedNewton2MississispiUnitedNewton3MississispiUnitedNewton4MississippiUnitedNewton5MississippiUnitedNewton6MississippiUnitedPontoc1MississippiUnitedPontoc2MississippiUnitedWest Jackson County1–2MississippiUnitedWey chauserMississippiUnitedUnitedColumbiaMontanaUnitedButteMontanaUnitedIncline Village1NevadaUnitedIncline Village1NevadaUnitedIncline Village1NevadaUnitedIncline Village3NevadaUnitedIncline Village5NevadaUnitedIncline Village5NevadaUnitedIncline Village6NevadaUnitedIncline Village7NevadaUnitedIncline Village7NevadaUnitedIncline Village7NevadaUnitedIncline Village1North CarolinaUnitedIncline Village7NevadaUnitedIncline Village1North CarolinaUnitedIncline Village1North CarolinaUnitedIncline Village1North CarolinaUnitedIncline Village1North CarolinaUnited   | /      |
|--|--------|
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| Newton       5       Mississippi       United 1         Newton       6       Mississippi       United 1         Pontotoc       1       Mississippi       United 1         Pontotoc       2       Mississippi       United 1         West Jackson County       1–2       Mississippi       United 1         Weyerhauser       Mississippi       United 1         Columbia       Montana       United 1         Incline Village       1       Nevada       United 1         Incline Village       1       Nevada       United 1         Incline Village       3       Nevada       United 1         Incline Village       4       Nevada       United 1         Incline Village       5       Nevada       United 1         Incline Village       6       Nevada       United 1         Incline Village       7       Nevada       United 1         Incline Village  | States |
| Newton       6       Mississippi       United         Pontotoc       1       Mississippi       United         Pontotoc       2       Mississippi       United         Pontotoc       2       Mississippi       United         West Jackson County       1–2       Mississispi       United         West Jackson County       T:1–7       Mississispi       United         West Jackson County       T:1–7       Mississispi       United         Columbia       Mostana       United       Incline Village       1       Nevada       United         Incline Village       2       Nevada       United       Incline Village       3       Nevada       United         Incline Village       5       Nevada       United       Incline Village       6       Nevada       United         Incline Village       7       Nevada       United       Incline Village       7       Nevada       United         Incline Village       7       Nevada       United       Incline Village       1       Nevada       United         Brookhaven       Meadow Marsh Pond System       New York       United       Incline Village       1       North Carolina       United <tr< td=""><td>States</td></tr<>  | States |
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| Pontotoc         2         Mississippi         United           West Jackson County         1–2         Mississippi         United           West Jackson County         T:1–7         Mississippi         United           Weyerhauser         Mississippi         United           Columbia         Missouri         United           Butte         Montana         United           Incline Village         1         Nevada         United           Incline Village         3         Nevada         United           Incline Village         4         Nevada         United           Incline Village         5         Nevada         United           Incline Village         6         Nevada         United           Incline Village         7   | States |
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| West Jackson County       T:1-7       Mississippi       United 1         Weyerhauser       Mississippi       United 1         Butte       Montana       United 1         Butte       Montana       United 1         Incline Village       1       Nevada       United 1         Incline Village       2       Nevada       United 1         Incline Village       3       Nevada       United 1         Incline Village       6       Nevada       United 1         Incline Village       6       Nevada       United 2         Incline Village       7       Nevada       United 1         Incline Village       7       Nevada       United 2         Incline Village       1       New York       United 2         Incline Village       1       New York       United 2         Incline Village       1       North Carolina       United 2         Seneca Army Depot  | States |
| Weyerhauser       Mississippi       United 1         Columbia       Missouri       United 1         Butte       Montana       United 1         Incline Village       1       Nevada       United 1         Incline Village       2       Nevada       United 1         Incline Village       3       Nevada       United 1         Incline Village       4       Nevada       United 1         Incline Village       6       Nevada       United 2         Incline Village       7       Nevada       United 2         Inondequoit Creek       New York <td>States</td>  | States |
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| Butte       Montana       United         Incline Village       1       Nevada       United         Incline Village       2       Nevada       United         Incline Village       3       Nevada       United         Incline Village       4       Nevada       United         Incline Village       5       Nevada       United         Incline Village       6       Nevada       United         Incline Village       7       Nevada       United         Brookhaven       Meadow Marsh Pond System       New York       United         Inondequoit Creek       New York       United       New York       United         Moodna Basin       New York       United       Seneca Army Depot       New York       United         Duplin County       1  | States |
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| Incline Village 2 Nevada United 1<br>Incline Village 3 Nevada United 1<br>Incline Village 4 Nevada United 1<br>Incline Village 5 Nevada United 1<br>Incline Village 6 Nevada United 1<br>Incline Village 7 Nevada United 1<br>Brokhaven Meadow Marsh Pond System New York United 2<br>Irondequoit Creek New York United 2<br>Monroe County New York United 2<br>Moodna Basin New York United 2<br>Duplin County 1 Novrk Carolina United 2<br>Duplin County 2 Novrth Carolina United 2<br>Duplin County 4 North Carolina United 2<br>Greensboro North Carolina United 2<br>Hilton Head Plantation Whooping Crane North Carolina United 2<br>Hilton Head Plantation Whooping Crane North Carolina United 2<br>New Hanover Township Treated North Carolina United 4<br>Hilton Head Plantation Whooping Crane North Carolina United 5<br>New Hanover Township Treated North Carolina United 5<br>Minot North Dakota United 5<br>Mandan North Dakota United 5<br>Mand | States |
| Incline Village 3 Nevada United 1<br>Incline Village 4 Nevada United 1<br>Incline Village 5 Nevada United 1<br>Incline Village 6 Nevada United 1<br>Incline Village 6 Nevada United 1<br>Incline Village 7 Nevada United 1<br>Monda Basin New York United 1<br>Seneca Army Depot New York United 1<br>Duplin County 1 New York United 1<br>Duplin County 2 North Carolina United 1<br>Duplin County 3 North Carolina United 2<br>Duplin County 4 North Carolina United 2<br>Greensboro North Carolina United 3<br>Herrings North Carolina United 4<br>New Hanover Township Raw North Carolina United 5<br>Sea Pines Boggy Gut North Carolina United 5<br>Sea Pines Boggy Gut North Carolina United 5<br>Minot North Dakota United 5<br>Minot North Dakota United 5<br>Franklin County Ohio United 5<br>Franklin County Ohio United 5   | States |
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| Incline Village 5 Nevada United 1<br>Incline Village 6 Nevada United 1<br>Incline Village 6 Nevada United 1<br>Incline Village 7 Nevada United 1<br>Incline Village 7 Nevada United 1<br>Brookhaven Meadow Marsh Pond System New York United 1<br>Irondequoit Creek New York United 1<br>Monroe County New York United 1<br>Moodna Basin New York United 2<br>Moodna Basin New York United 2<br>Seneca Army Depot New York United 2<br>Duplin County 1 North Carolina United 2<br>Duplin County 2 North Carolina United 2<br>Duplin County 3 North Carolina United 2<br>Duplin County 4 North Carolina United 2<br>Greensboro North Carolina United 3<br>Herrings North Carolina United 3<br>Herrings North Carolina United 3<br>New Hanover Township Raw North Carolina United 3<br>New Hanover Township Treated North Carolina United 3<br>Sea Pines Boggy Gut North Carolina United 3<br>Methana North Dakota United 3<br>Mandan North Dakota United 4<br>Minot North Dakota United 5<br>Franklin County Ohio United 5  | States |
| Incline Village0NevalaUnitedIncline Village6NevadaUnitedIncline Village7NevadaUnitedBrookhavenMeadow Marsh Pond SystemNew YorkUnitedIrondequoit CreekNew YorkUnitedMonroe CountyNew YorkUnitedMoodna BasinNew YorkUnitedMoodna BasinNew YorkUnitedSeneca Army DepotNew YorkUnitedDuplin County1North CarolinaUnitedDuplin County2North CarolinaUnitedDuplin County3North CarolinaUnitedDuplin County4North CarolinaUnitedHerringsNorth CarolinaUnitedHilton Head PlantationWhooping CraneNorth CarolinaUnitedNew Hanover TownshipTreatedNorth CarolinaUnitedSea PinesBoggy GutNorth CarolinaUnitedHillsboroNorth DakotaUnitedMorth CarolinaUnitedFranklin CountyOhioUnitedMorth DakotaUnitedFranklin CountyOhioUnitedMorth DakotaUnited  | States |
| Incline Vinlage0NevadaUnitedIncline Village7NevadaUnitedBrookhavenMeadow Marsh Pond SystemNew YorkUnitedIrondequoit CreekNew YorkUnitedMonroe CountyNew YorkUnitedMoodna BasinNew YorkUnitedSeneca Army DepotNew YorkUnitedDuplin County1North CarolinaUnitedDuplin County2North CarolinaUnitedDuplin County3North CarolinaUnitedDuplin County4North CarolinaUnitedHerringsNorth CarolinaUnitedHilton Head PlantationWhooping CraneNorth CarolinaUnitedNew Hanover TownshipTreatedNorth CarolinaUnitedSea PinesBoggy GutNorth CarolinaUnitedHillsboroNorth DakotaUnited1Franklin CountyOhioUnited1Franklin CountyOhioUnited1Sea PinesNorth DakotaUnited1Sea PinesBoggy GutNorth DakotaUnitedStandardNorth DakotaUnited1Sea PinesBoggy GutNorth DakotaUnitedSea PinesBoggy GutNorth DakotaUnitedStandardNorth DakotaUnited1StandardNorth DakotaUnited1StandardNorth DakotaUnited1StandardNorth DakotaUnited1 <td>States</td>  | States |
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| Duplin County2North CarolinaUnited isDuplin County3North CarolinaUnited isDuplin County4North CarolinaUnited isGreensboroNorth CarolinaUnited isHerringsNorth CarolinaUnited isHilton Head PlantationWhooping CraneNorth CarolinaNew Hanover TownshipRawNorth CarolinaUnited isNew Hanover TownshipTreatedNorth CarolinaUnited isSea PinesBoggy GutNorth CarolinaUnited isHillsboroNorth DakotaUnited isInited isMandanNorth DakotaUnited isInited isFranklin CountyOhioUnited isInited isFranklin CountyOhioUnited isInited is </td <td>States</td>   | States |
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| Dupin County4North CarolinaUnitedGreensboroNorth CarolinaUnitedHerringsNorth CarolinaUnitedHilton Head PlantationWhooping CraneNorth CarolinaUnitedNew Hanover TownshipRawNorth CarolinaUnitedNew Hanover TownshipTreatedNorth CarolinaUnitedSea PinesBoggy GutNorth CarolinaUnitedHillsboroNorth DakotaUnitedMorth DakotaUnitedMandanNorth DakotaUnitedFranklin CountyOhioUnitedFranklin CountyOhioUnitedMorth CarolinaUnited   | totos  |
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| HerringsNorth CarolinaUnitedHilton Head PlantationWhooping CraneNorth CarolinaUnitedNew Hanover TownshipRawNorth CarolinaUnitedNew Hanover TownshipTreatedNorth CarolinaUnitedSea PinesBoggy GutNorth CarolinaUnitedHillsboroNorth DakotaUnitedMandanNorth DakotaUnitedFranklin CountyOhioUnitedFranklin CountyOhioUnited  | totos  |
| Initial Head Planationwhooping CraneNorth CarolinaUnitedNew Hanover TownshipRawNorth CarolinaUnitedNew Hanover TownshipTreatedNorth CarolinaUnitedSea PinesBoggy GutNorth CarolinaUnitedHillsboroNorth DakotaUnitedMandanNorth DakotaUnitedFranklin CountyOhioUnitedFranklin CountyOhioUnited  | tates  |
| New Hanover TownshipRawNorth CarolinaUnited isNew Hanover TownshipTreatedNorth CarolinaUnited isSea PinesBoggy GutNorth CarolinaUnited isHillsboroNorth DakotaUnited isMandanNorth DakotaUnited isMinotNorth DakotaUnited isFranklin CountyOhioUnited isFranklin CountyOhioUnited is   | states |
| New Hanover Township     Treated     North Carolina     United       Sea Pines     Boggy Gut     North Carolina     United       Hillsboro     North Dakota     United       Mandan     North Dakota     United       Minot     North Dakota     United       Franklin County     Ohio     United  |        |
| Sea Prices     Boggy Gut     North Carolina     United in the second s   | states |
| Hillsboro     North Dakota     United 3       Mandan     North Dakota     United 3       Minot     North Dakota     United 3       Franklin County     Ohio     United 3       Franklin County     Ohio     United 3   | states |
| Mandan     North Dakota     United 3       Minot     North Dakota     United 3       Franklin County     Ohio     United 3       Franklin County     Ohio     United 3   | states |
| Minot     North Dakota     Onited 3       Franklin County     Ohio     United 3       Franklin County     Ohio     United 3  | states |
| Franklin County     Onio     United S       Franklin County     Ohio     United S  | states |
| Franklin County Onio United S  | states |
|  | states |
| LICK KUN Ohio United   | states |
| Olentangy I Ohio United  | nates  |
| Olentangy 2 Ohio United  | states |
| Cannon Beach Oregon United   | states |
| Hillsboro Jackson Bottoms 1–17 Oregon United   | States |
| Mt. Angel Oregon United  | states |
| Oregon State University 1 Oregon United S  | states |
| Oregon State University 2 Oregon United S  | states |
| Oregon State University 3 Oregon United S  | states |
| Oregon State University 4 Oregon United S  | states |
| Oregon State University 5 Oregon United S  | states |
| Oregon State University 6 Oregon United S  | states |
| Silverton Oregon United  | states |

| FWS System Name    | Identifier  | State/Province | Country       |
|--------------------|-------------|----------------|---------------|
| Conestoga          |             | Pennsylvania   | United States |
| Cumberland County  |             | Pennsylvania   | United States |
| Friendship Hill    |             | Pennsylvania   | United States |
| Iselin             |             | Pennsylvania   | United States |
| Neshaminy          |             | Pennsylvania   | United States |
| Palmerton          |             | Pennsylvania   | United States |
| Springdale         |             | Pennsylvania   | United States |
| Central Slough     | T:1         | South Carolina | United States |
| Savannah River     |             | South Carolina | United States |
| Vereen             | Bear Bay 1  | South Carolina | United States |
| Arlington          |             | South Dakota   | United States |
| Alcoa              | Blue Pond   | Tennessee      | United States |
| Alcoa              | Duck Spring | Tennessee      | United States |
| Milan              |             | Tennessee      | United States |
| Beaumont           |             | Texas          | United States |
| Tarrant            | 1           | Texas          | United States |
| Tarrant            | 2           | Texas          | United States |
| Tarrant            | 3           | Texas          | United States |
| Tarrant            | 4           | Texas          | United States |
| Tarrant            | 5           | Texas          | United States |
| Tarrant            | 6           | Texas          | United States |
| Tarrant            | 7           | Texas          | United States |
| Tarrant            | 8           | Texas          | United States |
| Tarrant            | 9           | Texas          | United States |
| Victoria           |             | Texas          | United States |
| Crestwood          |             | Virginia       | United States |
| Franklin Farms     |             | Virginia       | United States |
| Bellevue           |             | Washington     | United States |
| Connell            | Pilot       | Washington     | United States |
| Connell            | Full        | Washington     | United States |
| Renton             |             | Washington     | United States |
| Albright           |             | West Virginia  | United States |
| Brillion           |             | Wisconsin      | United States |
| David Gerrits Farm | 1 & 2       | Wisconsin      | United States |
| David Gerrits Farm | 3 & 4       | Wisconsin      | United States |
| Drummond           |             | Wisconsin      | United States |
| Lake Nebagamon     |             | Wisconsin      | United States |

#### TABLE A.2 Horizontal Subsurface Flow Wetlands

| HSSF System Name | Identifier | State/Province  | Country   |
|------------------|------------|-----------------|-----------|
| Lismore          | GB1        | New South Wales | Australia |
| Lismore          | GB2        | New South Wales | Australia |
| Richmond         | Gravel     | New South Wales | Australia |
| Richmond         | Mix A      | New South Wales | Australia |
| Richmond         | Mix B      | New South Wales | Australia |
| Richmond         | Schoeno    | New South Wales | Australia |
| Richmond         | Typha      | New South Wales | Australia |
| Brisbane         | А          | Queensland      | Australia |
| Brisbane         | В          | Queensland      | Australia |
| Brisbane         | С          | Queensland      | Australia |
| HSSF System Name        | Identifier  | State/Province | Country        |
|-------------------------|-------------|----------------|----------------|
| Brisbane                | D           | Queensland     | Australia      |
| Alstonville             |             |                | Australia      |
| Edmonton                |             | Alberta        | Canada         |
| Princeport              |             | Nova Scotia    | Canada         |
| Monteverde              | 1           |                | Costa Rica     |
| Monteverde              | 2           |                | Costa Rica     |
| Brehov                  |             |                | Czech Republic |
| Chmelna                 |             |                | Czech Republic |
| Doksy                   |             |                | Czech Republic |
| Kacice                  |             |                | Czech Republic |
| Koberovy                |             |                | Czech Republic |
| Kolodeje                |             |                | Czech Republic |
| Krucemburk              |             |                | Czech Republic |
| Liszny                  |             |                | Czech Republic |
| Morina                  |             |                | Czech Republic |
| Nucice                  |             |                | Czech Republic |
| Ondrejov                |             |                | Czech Republic |
| Onsov                   |             |                | Czech Republic |
| Osova Bityyska          |             |                | Czech Republic |
| Velescice               |             |                | Czech Republic |
| Zintenice               |             |                | Czech Republic |
| Abu Attwa               |             |                | Egypt          |
| Ismalia                 |             |                | Egypt          |
| Brandenburg             |             |                | Germany        |
| Jülich                  | Phragmites  |                | Germany        |
| Jülich                  | Typha       |                | Germany        |
| Langenreichenbach       |             |                | Germany        |
| Wiedersburg             |             |                | Germany        |
| Thrace                  | MG-Z        |                | Greece         |
| Thrace                  | MG-C        |                | Greece         |
| Thrace                  | MG-R        |                | Greece         |
| Sakhnin                 |             |                | Israel         |
| Cecchi                  |             |                | Italy          |
| Chiampo Valley          | Phragmites  |                | Italy          |
| Chiampo Valley          | Carex       |                | Italy          |
| Florence                |             |                | Italy          |
| La Croce                |             |                | Italy          |
| Ornellaia               |             |                | Italy          |
| Putignano               |             |                | Italy          |
| San Michele de Ganzaria |             |                | Italy          |
| Akumal                  |             |                | Mexico         |
| Pachuaca                |             |                | Mexico         |
| UNAM                    |             |                | Mexico         |
| Rabat                   |             |                | Morocco        |
| Drury                   |             |                | New Zealand    |
| Hamilton                | 1 Bulrush   |                | New Zealand    |
| Hamilton                | 1 Unplanted |                | New Zealand    |
| Hamilton                | 2 Bulrush   |                | New Zealand    |
| Hamilton                | 2 Unplanted |                | New Zealand    |
| Hamilton                | 3 Bulrush   |                | New Zealand    |
| Hamilton                | 3 Unplanted |                | New Zealand    |
| Hamilton                | 4 Bulrush   |                | New Zealand    |
| Hamilton                | 4 Unplanted |                | New Zealand    |

(Continued)

| HSSF System Name | Identifier | State/Province | Country        |
|------------------|------------|----------------|----------------|
| Hamilton         | 5 Bulrush  |                | New Zealand    |
| Hamilton         | Dairy 1    |                | New Zealand    |
| Hamilton         | Dairy 2    |                | New Zealand    |
| Hamilton         | Dairy 3    |                | New Zealand    |
| Hamilton         | Dairy 4    |                | New Zealand    |
| Hamilton         | Dairy 5    |                | New Zealand    |
| Hamilton         | Meat 1     |                | New Zealand    |
| Hamilton         | Meat 2     |                | New Zealand    |
| Hamilton         | Meat 3     |                | New Zealand    |
| Hamilton         | M1         |                | New Zealand    |
| Hamilton         | D1         |                | New Zealand    |
| Hamilton         | D2         |                | New Zealand    |
| Hamilton         | D2A        |                | New Zealand    |
| Omaha            |            |                | New Zealand    |
| Opononi          |            |                | New Zealand    |
| Waipoua          |            |                | New Zealand    |
| Fagerness        |            |                | Norway         |
| Haugstein        |            |                | Norway         |
| Jølle            |            |                | Norway         |
| Jordforsk        |            |                | Norway         |
| Ostegarden       |            |                | Norway         |
| Stange           |            |                | Norway         |
| Tveter           | 1          |                | Norway         |
| Tveter           | 2          |                | Norway         |
| Golczew          |            |                | Poland         |
| Gralewo          |            |                | Poland         |
| Gronowo          |            |                | Poland         |
| Lubiejewo        |            |                | Poland         |
| Nieskorz         |            |                | Poland         |
| Nieskorz         |            |                | Poland         |
| Rokitno          |            |                | Poland         |
| Rviewo           |            |                | Poland         |
| Mpophomeni       |            |                | South Africa   |
| Pretoria         | 1          |                | South Africa   |
| Pretoria         | 2          |                | South Africa   |
| Pretoria         | 3          |                | South Africa   |
| Barcelona        | Al         |                | Spain          |
| Barcelona        | A2         |                | Spain          |
| Barcelona        | B1         |                | Spain          |
| Barcelona        | B2         |                | Spain          |
| Barcelona        | <u>C1</u>  |                | Spain          |
| Barcelona        | C2         |                | Spain          |
| Barcelona        | D1         |                | Spain          |
| Barcelona        | D2         |                | Spain          |
| Dar es Salaam    | 1          |                | Tanzania       |
| Dar es Salaam    | 2          |                | Tanzania       |
| Chiang Mai       |            |                | Thailand       |
| Pathumthani      |            |                | Thailand       |
| Acle             |            |                | United Kingdom |
| Ashby Folville   |            |                | United Kingdom |
| Audlem           | 1          |                | United Kingdom |
| Audlem           | 2          |                | United Kingdom |
| Audlem           | 3          |                | United Kingdom |
| Audlem           | 4          |                | United Kingdom |
|                  |            |                |                |

| HSSF System Name         | Identifier | State/Province | Country        |
|--------------------------|------------|----------------|----------------|
| Audlem                   | 5          |                | United Kingdom |
| Audlem                   | 6          |                | United Kingdom |
| Audlem                   | 7          |                | United Kingdom |
| Audlem                   | 8          |                | United Kingdom |
| Audlem                   | 9          |                | United Kingdom |
| Audlem                   | 10         |                | United Kingdom |
| Broxted                  | Lower      |                | United Kingdom |
| Broxted                  | Upper      |                | United Kingdom |
| Budds Farm               | **         |                | United Kingdom |
| Castleroe                | 1          |                | United Kingdom |
| Castleroe                | 2          |                | United Kingdom |
| Castleroe                | 3          |                | United Kingdom |
| Castleroe                | 4          |                | United Kingdom |
| Castleroe                | Peat bed   |                | United Kingdom |
| Cherry Burton            |            |                | United Kingdom |
| Claverley                |            |                | United Kingdom |
| Culcrow                  | 1          |                | United Kingdom |
| Ditton Priors            |            |                | United Kingdom |
| Drointon                 |            |                | United Kingdom |
| Earlswood                |            |                | United Kingdom |
| Earlswood                |            |                | United Kingdom |
| East Haddon              | 2          |                | United Kingdom |
| East Haddon              |            |                | United Kingdom |
| Forton                   |            |                | United Kingdom |
| Freethorpe               |            |                | United Kingdom |
| Gailey                   |            |                | United Kingdom |
| Gravesend                | 1          |                | United Kingdom |
| Gravesend                | 2          |                | United Kingdom |
| Gravesend                | 3          |                | United Kingdom |
| Himley                   | 1          |                | United Kingdom |
| Himley                   | 2          |                | United Kingdom |
| Hognaston                | _          |                | United Kingdom |
| Holthy                   |            |                | United Kingdom |
| Kingston And Madley      |            |                | United Kingdom |
| Kirmington               |            |                | United Kingdom |
| Knowbury                 |            |                | United Kingdom |
| Leek Wootton             |            |                | United Kingdom |
| Lighthorne Heath         |            |                | United Kingdom |
| Little Stretton          |            |                | United Kingdom |
| Little Wenlock           |            |                | United Kingdom |
| Lydbury North (Old)      |            |                | United Kingdom |
| Malham                   |            |                | United Kingdom |
| Meltham                  |            |                | United Kingdom |
| Middleton (Shropshire)   |            |                | United Kingdom |
| Middleton (Warwickshire) |            |                | United Kingdom |
| Naseby                   |            |                | United Kingdom |
| Needingworth             |            |                | United Kingdom |
| Norton Lindsev           |            |                | United Kingdom |
| Nun Monkton              |            |                | United Kingdom |
| Oaklands Park            | 1          |                | United Kingdom |
| Oaklands Park            | 2          |                | United Kingdom |
| Rugelev                  | -          |                | United Kingdom |
| Saxby                    |            |                | United Kingdom |
|                          |            |                | (Continued)    |

| HSSF System Name     | Identifier | State/Province | Country        |
|----------------------|------------|----------------|----------------|
| Southwick            | 2          |                | United Kingdom |
| Southwick            | 3          |                | United Kingdom |
| Stockley             | 1          |                | United Kingdom |
| Stockley             | 2          |                | United Kingdom |
| Stocklev             | 3          |                | United Kingdom |
| Thorpe Satchville    |            |                | United Kingdom |
| Vallevfield          | 1          |                | United Kingdom |
| Valleyfield          | 2          |                | United Kingdom |
| Valleyfield          | 3          |                | United Kingdom |
| Valleyfield          | 1          |                | United Kingdom |
| Wentworth Castle     |            |                | United Kingdom |
| Wentworth Castle     | 2          |                | United Kingdom |
| Wentworth Castle     | 2          |                | United Kingdom |
| Wentworth Castle     | 3          |                | United Kingdom |
| Wentworth Cashe      | 4          |                |                |
| west Harwood         | 1          |                |                |
| westow               | 1          |                |                |
| Westow               | 2          |                | United Kingdom |
| Wetwood              |            |                | United Kingdom |
| Alabama              | 1          | Alabama        | United States  |
| Alabama              | 2          | Alabama        | United States  |
| Alabama              | 3          | Alabama        | United States  |
| Alabama              | 4          | Alabama        | United States  |
| Degussa Corporation  |            | Alabama        | United States  |
| Phillips High School |            | Alabama        | United States  |
| Pima County          |            | Arizona        | United States  |
| Sahuarita            |            | Arizona        | United States  |
| Tubac                |            | Arizona        | United States  |
| Wickenburg           |            | Arizona        | United States  |
| Clarendon            |            | Arkansas       | United States  |
| Dierks               |            | Arkansas       | United States  |
| Foreman              |            | Arkansas       | United States  |
| Gould                |            | Arkansas       | United States  |
| Gurndon              |            | Arkansas       | United States  |
| Judsonia             |            | Arkansas       | United States  |
| Lewisville           |            | Arkansas       | United States  |
| North Crossett       |            | Arkansas       | United States  |
| Ola                  |            | Arkansas       | United States  |
| Pocahontas           |            | Arkansas       | United States  |
| Rector               | 1          | Arkansas       | United States  |
| Rector               | 2          | Arkansas       | United States  |
| Smackover            |            | Arkansas       | United States  |
| Tuckema              |            | Arkansas       | United States  |
| Waldo                |            | Arkansas       | United States  |
| Hopland              |            | California     | United States  |
| Oxnard               | Train 1    | California     | United States  |
| Oxnard               | Train 7    | California     | United States  |
| Sacramento           | 11         | California     | United States  |
| Santee               | Graval     | California     | United States  |
| Santee               | Cottoil    | California     | United States  |
| Santee               | Bulmah     | California     | United States  |
| Santee               | Dunusii    | California     | United States  |
| Calaban              | rmagnines  | Calorada       | United States  |
| Calallall            |            | Colorado       | United States  |

| HSSF System Name                 | Identifier | State/Province | Country       |
|----------------------------------|------------|----------------|---------------|
| Highland Acres W&S District      |            | Colorado       | United States |
| Las Animas                       |            | Colorado       | United States |
| Fish Royer                       |            | Indiana        | United States |
| Anamosa                          |            | Iowa           | United States |
| Beery                            |            | Kansas         | United States |
| Brown                            |            | Kansas         | United States |
| Carlson                          |            | Kansas         | United States |
| Manhattan                        | PFL        | Kansas         | United States |
| Manhattan                        | PCL        | Kansas         | United States |
| Manhattan                        | PCR        | Kansas         | United States |
| Manhattan                        | UFL        | Kansas         | United States |
| Manhattan                        | UCL        | Kansas         | United States |
| Manhattan                        | UCR        | Kansas         | United States |
| Anderson                         |            | Kentucky       | United States |
| Anderson County                  |            | Kentucky       | United States |
| Benton                           | 3          | Kentucky       | United States |
| Greenville                       | 1          | Kentucky       | United States |
| Greenville                       | 2          | Kentucky       | United States |
| Greenville                       | 3          | Kentucky       | United States |
| Greenville                       | 4          | Kentucky       | United States |
| Greenville                       | 5          | Kentucky       | United States |
| Hardin                           | 1          | Kentucky       | United States |
| Hardin                           | 2          | Kentucky       | United States |
| Paris                            |            | Kentucky       | United States |
| Scott                            |            | Kentucky       | United States |
| Denham Springs                   | 1          | Louisiana      | United States |
| Denham Springs                   | 2          | Louisiana      | United States |
| Denham Springs                   | 3          | Louisiana      | United States |
| Greenleaves Subdivision          |            | Louisiana      | United States |
| Haughton                         |            | Louisiana      | United States |
| Mandeville                       |            | Louisiana      | United States |
| Keyser's Ridge                   |            | Maryland       | United States |
| Mayo Peninsula                   |            | Maryland       | United States |
| Cambridge-Isanti School District |            | Minnesota      | United States |
| Carlson Residence                |            | Minnesota      | United States |
| Cedar Mills                      |            | Minnesota      | United States |
| Chisholm                         |            | Minnesota      | United States |
| Clearwater Forest                |            | Minnesota      | United States |
| Darfur                           |            | Minnesota      | United States |
| Delft                            |            | Minnesota      | United States |
| Eichten Cheese                   |            | Minnesota      | United States |
| Fields of St. Croix - North      |            | Minnesota      | United States |
| Grand Lake                       |            | Minnesota      | United States |
| Happiness Resort                 |            | Minnesota      | United States |
| Jackson Meadow                   | South      | Minnesota      | United States |
| Jackson Meadow                   | North      | Minnesota      | United States |
| Lake Elmo                        |            | Minnesota      | United States |
| Lakes of Fairhaven               |            | Minnesota      | United States |
| Lake Washington                  |            | Minnesota      | United States |
| Lutsen East Flank                |            | Minnesota      | United States |
| Lutsen Sea Villas                |            | Minnesota      | United States |
| Morton Farm Preserve             |            | Minnesota      | United States |
| Mulberry Meadows                 |            | Minnesota      | United States |

(Continued)

| HSSF System Name              | Identifier  | State/Province | Country       |
|-------------------------------|-------------|----------------|---------------|
| NAWE Office                   |             | Minnesota      | United States |
| NERCC                         | 1           | Minnesota      | United States |
| NERCC                         | 2           | Minnesota      | United States |
| The Ponds                     |             | Minnesota      | United States |
| The Preserve                  |             | Minnesota      | United States |
| Northern Tier High Adventure  |             | Minnesota      | United States |
| Base                          |             |                |               |
| Opole                         |             | Minnesota      | United States |
| Prairie Hamlet                |             | Minnesota      | United States |
| Prinsburg                     |             | Minnesota      | United States |
| Spring Hill                   |             | Minnesota      | United States |
| St. George                    |             | Minnesota      | United States |
| Super America - Ham Lake      |             | Minnesota      | United States |
| Super America - Wyoming       |             | Minnesota      | United States |
| Tamarack                      |             | Minnesota      | United States |
| Tamarack Farm Estates         |             | Minnesota      | United States |
| Wildflower Shores             |             | Minnesota      | United States |
| Columbus                      |             | Mississippi    | United States |
| Utica, North                  | 1           | Mississippi    | United States |
| Utica, North                  | 2           | Mississippi    | United States |
| Utica, South                  | 1           | Mississippi    | United States |
| Utica, South                  | 2           | Mississippi    | United States |
| Lake Capri                    | Vegetated   | Missouri       | United States |
| Lake Capri                    | Unvegetated | Missouri       | United States |
| Firethorn                     |             | Nebraska       | United States |
| Lincoln                       |             | Nebraska       | United States |
| Albuquerque                   |             | New Mexico     | United States |
| Minoa                         | 1           | New York       | United States |
| Minoa                         | 2           | New York       | United States |
| Minoa                         | 3           | New York       | United States |
| Craven County                 |             | North Carolina | United States |
| North Carolina Ranger Station |             | North Carolina | United States |
| North Carolina Residence      | 1           | North Carolina | United States |
| North Carolina Residence      | 2           | North Carolina | United States |
| Ohio Residences               | 13          | Ohio           | United States |
| Ohio Residences               | 14          | Ohio           | United States |
| Ohio Residences               | 15          | Ohio           | United States |
| Ohio Residences               | 16          | Ohio           | United States |
| Ohio Residences               | 17          | Ohio           | United States |
| Ohio Residences               | 19          | Ohio           | United States |
| Ohio Residences               | 20          | Ohio           | United States |
| Ohio Residences               | 21          | Ohio           | United States |
| Halsey                        |             | Oregon         | United States |
| Iselin                        |             | Pennsylvania   | United States |
| Baxter                        | А           | Tennessee      | United States |
| Baxter                        | В           | Tennessee      | United States |
| Baxter                        | С           | Tennessee      | United States |
| Baxter                        | D           | Tennessee      | United States |
| Baxter                        | Е           | Tennessee      | United States |
| Baxter                        | F           | Tennessee      | United States |
| Baxter                        | G           | Tennessee      | United States |
| Baxter                        | Н           | Tennessee      | United States |
| Baxter                        | Ι           | Tennessee      | United States |
| Baxter                        | J           | Tennessee      | United States |

| HSSF System Name        | Identifier | State/Province | Country       |
|-------------------------|------------|----------------|---------------|
| Baxter                  | К          | Tennessee      | United States |
| Baxter                  | L          | Tennessee      | United States |
| Baxter                  | М          | Tennessee      | United States |
| Baxter                  | Ν          | Tennessee      | United States |
| Kingston Power Plant    |            | Tennessee      | United States |
| Bryan                   |            | Texas          | United States |
| College Station         |            | Texas          | United States |
| Dessau Mobile Home Park |            | Texas          | United States |
| D'Harris                |            | Texas          | United States |
| Dublin                  |            | Texas          | United States |
| Houston                 |            | Texas          | United States |
| Johnson City            | 1          | Texas          | United States |
| Johnson City            | 2          | Texas          | United States |
| Stephenville            |            | Texas          | United States |
| Tomball                 |            | Texas          | United States |
| Weslaco                 |            | Texas          | United States |
| Kentland                | 1          | Virginia       | United States |
| Kentland                | 2          | Virginia       | United States |
| Kentland                | 3          | Virginia       | United States |
| Kentland                | СТ         | Virginia       | United States |
| Kentland                | WG         | Virginia       | United States |
| Monterey                |            | Virginia       | United States |
| Monterrey               |            | Virginia       | United States |
| Powell                  | 1          | Virginia       | United States |
| Powell                  | 2          | Virginia       | United States |
| Powell                  | 3          | Virginia       | United States |
| Powell                  | СТ         | Virginia       | United States |
| Powell                  | WG         | Virginia       | United States |
| Dungeness               |            | Washington     | United States |
| Morgantown              |            | West Virginia  | United States |
| St. Croix Chippewa      |            | Wisconsin      | United States |

# TABLE A.3 Vertical Flow Wetlands

| VF System Name           | Identifier | State/Province | Country |
|--------------------------|------------|----------------|---------|
| Ernsthofen               |            |                | Austria |
| Gleisdorf (Binder)       |            |                | Austria |
| Hollerberg-West          |            |                | Austria |
| Horbach                  |            |                | Austria |
| Lappach (Kurzmann)       |            |                | Austria |
| Wolfern                  |            |                | Austria |
| YX                       |            |                | Austria |
| Strengberg               |            |                | Austria |
| Birkfeld (Hoeller)       |            |                | Austria |
| Lasnitzhöhe (Laposa)     |            |                | Austria |
| Lang Fr.                 |            |                | Austria |
| Jennersdorf (Doppelhofer | )          |                | Austria |
| Pischelsdorf (Hart)      |            |                | Austria |
| Hart b. Graz (Koberg)    |            |                | Austria |
| Zeutschach (Hofer)       |            |                | Austria |
|                          |            |                |         |

# TABLE A.3 (CONTINUED) Vertical Flow Wetlands

| VF System Name        | Identifier | State/Province | Country     |
|-----------------------|------------|----------------|-------------|
| Bokrijk               |            |                | Belgium     |
| PDLT                  |            |                | Belgium     |
| PIME                  |            |                | Belgium     |
| Sint-Niklass Heimolen |            |                | Belgium     |
| System A              |            |                | Belgium     |
| System B              |            |                | Belgium     |
| System C              |            |                | Belgium     |
| System D              |            |                | Belgium     |
| System E              |            |                | Belgium     |
| Zemst-Larbeek         |            |                | Belgium     |
| Blenterin             |            | Ontario        | Canada      |
| Vinland               |            | Ontario        | Canada      |
| Ansaster              |            |                | Canada      |
| Saint Ann's           |            |                | Canada      |
| Saint Andrés          |            |                | Colombia    |
| Bijar Cres            |            |                | Croatia     |
| Aarhus                |            |                | Denmark     |
| Paistu                |            |                | Estonia     |
| Roussillon            |            |                | France      |
| Saint Thomé           |            |                | France      |
| Langenreichenbach     |            |                | Germany     |
| Langemenenenbaen      |            |                | Germany     |
| Casolara Acqua Chiara |            |                | Italy       |
| Carbaia<br>Carbaia    |            |                | Italy       |
| Cerbaia               |            |                | Italy       |
| Contrada Patrasa      |            |                | Italy       |
| Eirongo Hotal BC      |            |                | Italy       |
| Flienze, notel KC     |            |                | Italy       |
| Cariaia               |            |                |             |
|                       |            |                |             |
|                       |            |                | Namel       |
|                       |            |                | Nepal       |
| Adema                 |            |                | Netherlands |
| Appeischa             |            |                | Netherlands |
| Boxtel                |            |                | Netherlands |
| Deurna                |            |                | Netherlands |
| Groot Ehrental        |            |                | Netherlands |
| Hamming               |            |                | Netherlands |
| Heislum               |            |                | Netherlands |
| Hobbitstee            |            |                | Netherlands |
| Klein Profijt         |            |                | Netherlands |
| Koudum                |            |                | Netherlands |
| Lauersoog             |            |                | Netherlands |
| Lemmer                |            |                | Netherlands |
| Nijkerk               |            |                | Netherlands |
| Nooyen                |            |                | Netherlands |
| Onnes                 |            |                | Netherlands |
| Oosthem               |            |                | Netherlands |
| Oud-Beijerland        |            |                | Netherlands |
| Oudega                |            |                | Netherlands |
| Spijkerman            |            |                | Netherlands |
| ter Veer              |            |                | Netherlands |
| Terpstra              |            |                | Netherlands |
| van Oirschot          |            |                | Netherlands |

| TABLE A  | .3            |  |
|----------|---------------|--|
| Vertical | Flow Wetlands |  |

| VF System Name         | Identifier | State/Province | Country        |
|------------------------|------------|----------------|----------------|
| van Ravenhorst         |            |                | Netherlands    |
| Veening                |            |                | Netherlands    |
| Vrieling               |            |                | Netherlands    |
| Wapserveen             |            |                | Netherlands    |
| Fagernes               |            |                | Norway         |
| Haugstein              |            |                | Norway         |
| Jolle                  |            |                | Norway         |
| Østergårde             |            |                | Norway         |
| Tveter I               |            |                | Norway         |
| Carion de los Céspedes |            |                | Spain          |
| Mojacar                |            |                | Spain          |
| Castleroe              | Gravel bed |                | United Kingdom |
| Castleroe              | Peat bed   |                | United Kingdom |
| Drointon               | 1          |                | United Kingdom |
| Drointon               | 2          |                | United Kingdom |
| Gailey                 |            |                | United Kingdom |
| Medmenham              | 1          |                | United Kingdom |
| Medmenham              | 2          |                | United Kingdom |
| Oaklands Park          | 1          |                | United Kingdom |
| Oaklands Park          | 2          |                | United Kingdom |
| Rugeley                | 1          |                | United Kingdom |
| Rugeley                | 2          |                | United Kingdom |
| Wills Barn             |            |                | United Kingdom |
| LaGrange County        |            | Indiana        | United States  |
| North Carolina School  |            | North Carolina | United States  |
| Laguna Niguel          |            | California     | United States  |
| Salem                  | Bed 1      | Oregon         | United States  |
| Salem                  | Bed 2      | Oregon         | United States  |
| Saginaw                |            | Michigan       | United States  |
| Connell                | Pilot      | Washington     | United States  |
| Connell                | Full scale | Washington     | United States  |

# Appendix B: Tracer Testing and Flow-Pattern Modeling

The large majority of information on the contaminant removal capabilities of treatment wetlands has been in the form of a relatively continuous time series of inlet and outlet concentrations, under conditions of known flow. There is a second realm of data acquisition and analysis that revolves around the spike addition of substances to the wetland. A wide variety of substances have been used to trace the progress of water through treatment wetlands. These have included the salt ions lithium, bromide, chloride, iodide, and fluoride; the fluorescent dyes rhodamine RWT and B fluorescein; and tritiated water. Most often, these are pulse injected into the wetland outlet. The purpose of hydraulic tracer testing is to determine the distribution of detention times for the wetland.

Detention time distributions (DTDs) for treatment wetlands have been extensively investigated at many wetland sites, and thus there exist numerous examples of the functional forms that are characteristic of wetlands. Single-shot tracer injection with effluent concentration monitoring is usually employed (Kadlec and Knight, 1996). Because the tracer does not (theoretically) interact with wetland soils or biota, it serves as a marker of the water with which it enters. Typical distributions are bell shaped, with some tracer exiting at short times, and some exiting at longer times.

This evidence is conclusive: imperfect flow patterns pervade the universe of treatment wetlands. It is necessary to account for this in design, and it is accomplished via nonideal flow models. In turn, the understanding and development of nonideal flow models derive principally from tracer testing. The purpose of this appendix is to expand on the practicalities, pitfalls, and results of wetland tracer testing.

One of the principal results derived from tracer testing is presented in Chapter 2—the volumetric efficiency of the wetland, i.e., how much of the nominal wetland water volume is involved in its flow. It is the ratio of tracer detention time to nominal detention time:  $e_v = \tau/\tau_n$ .

Another principal result is the dimensionless variance of the outlet response,  $\sigma_{\theta}^2$ , which is briefly discussed in Chapter 6. This measure of the spread of the distribution of detention times may be used in a number of ways as an aid to pollutant removal performance. The dimensionless variance may be used to determine the parameters in DTD models, such as the tanks-in-series (TIS) model. Or, it may be used to compute the DTD efficiency of the wetland (Persson *et al.*, 1999):

$$e_{\rm DTD} = \left(1 - \sigma_{\theta}^2\right) \tag{B.1}$$

This efficiency is unity for plug flow (PF), and zero for perfect mixing. As shown by Kadlec and Knight (1996), the DTD efficiency is an approximate interpolator between the performance of one TIS, as measured by  $F_{\rm ITIS}$ , and PF performance, as measured by  $F_{\rm PF}$ .

$$F = \frac{C - C^*}{C_{\rm i} - C^*} = e_{\rm DTD} \ F_{\rm PF} + (1 - e_{\rm DTD}) \ F_{\rm 1TIS}$$
(B.2)

For plug flow,

$$F_{\rm PF} = \frac{C_{\rm PF} - C^*}{C_{\rm i} - C^*} = \exp\left(\frac{-k_{\rm A}\tau}{h}\right) \tag{B.3}$$

For NTIS,

$$F_{\text{TIS}} = \frac{C_{\text{TIS}} - C^*}{C_{\text{i}} - C^*} = \left(1 + \frac{k_A \tau}{hN}\right)^{-N}$$
(B.4)

where

C =outlet concentration, mg/m<sup>3</sup>

 $C_i$  = average inlet concentration, mg/m<sup>3</sup>

 $C^*$  = background concentration, mg/m<sup>3</sup>

F = fraction remaining to background

 $k_{\rm A}$  = intrinsic reaction rate constant, m/d

N = number of tanks  $\tau =$  detention time, d

The root-mean-square degree of fit of the approximation for Equation B.2 ranges 1-6% for  $1 \le (k_A \tau/h) \le 3$ .

Persson *et al.* (1999) go on to suggest a combined measure, the hydraulic efficiency ( $\lambda$ ), that reflects the excluded volume and the mixing pattern of constructed wetlands. This measure is defined as the product of the volumetric efficiency and the DTD efficiency:

$$\lambda = e_{\rm V} \cdot e_{\rm DTD} \tag{B.5}$$

This is useful for ranking wetlands for their combined efficiency, but is not directly useful for parameter estimation. The two pieces are needed separately for quantitative estimates of performance. For a TIS model, the combined hydraulic efficiency is given by a very simple result:

$$\lambda = \frac{\tau_p}{\tau_n} \tag{B.6}$$

where

 $\tau_p$  = tracer peak time  $\tau_n$  = nominal hydraulic detention time Persson *et al.* (1999) have explored both real wetland systems and, via calibrated two-dimensional dynamic modeling, simulated situations. They found  $0.11 < \lambda < 0.90$ . The same parameter has been evaluated for other hypothetical wetland situations (Jenkins and Greenway, 2005).

# **IDEAL FLOW REACTORS**

Wetlands can be thought of as a cross section between two theoretically ideal reactors: the plug flow reactor and continuously-stirred tank reactor (CSTR). The plug flow (PF) reactor represents a situation where there is no internal mixing within the reactor, and water parcels move in unison from the inlet to the outlet. The CSTR represents the ideal of perfect mixing: water entering the system is instantaneously mixed throughout the reactor.

#### NOMINAL HYDRAULIC DETENTION TIME

PF and CSTR reactors behave very differently in response to the input of a conservative tracer. To discuss tracer behavior, it is useful to review the concepts of hydraulic detention time from Chapter 2. For a free water surface (FWS) wetland, the nominal wetland water volume is defined as the volume enclosed by the upper water surface, and the bottom and sides of the impoundment.

$$\tau_{\rm n} = \frac{V_{\rm n}}{Q} = \frac{(LWh)_{\rm n}}{Q} \tag{B.7}$$

where

 $\tau_n$  = nominal hydraulic detention time, days L = wetland length, m W = wetland width, m h = water depth, m  $LWh_n$  = nominal wetland volume, m<sup>3</sup> Q = flow rate, m<sup>3</sup>/d

For a subsurface flow (SSF) wetland, it is that enclosed volume multiplied by the porosity of the clean (unclogged) bed media.

$$\tau_{n} = \frac{V_{n}}{Q} = \frac{\varepsilon(LWh)_{n}}{Q}$$
(B.8)

where

 $\varepsilon$  = bed media porosity, dimensionless

Dimensionless time,  $\theta$ , can be used instead of nominal hydraulic detention time,  $\tau_n$ , when comparing tracer response curves:

$$\theta = \frac{t}{\tau_{\rm n}} \tag{B.9}$$

where

t = elapsed time in days

### TRACER RESPONSE IN PF AND CSTR REACTORS

A spike input of tracer entering a PF reactor will move through the system with zero mixing. As a result, the tracer spike will exit the reactor unchanged at  $\tau_n$  ( $\theta = 1$ ). In a CSTR reactor, the tracer impulse is instantaneously and uniformly distributed among the tank contents (Levenspiel, 1972). As flow continues to enter the tank, tracer-contaminated water is displaced, resulting in a declining tracer output curve with a long tail. Figure B.1 displays both types of ideal reactors and their associated tracer response curves.

#### **REAL-WORLD TRACER MOVEMENT**

It is well documented that the flow patterns through treatment wetland systems are nonideal and do not conform to either the PF or CSTR ideals (see Tables 6.1 and 6.2, Chapter 6). In SSF wetland systems, dispersion and mixing occurs within the bed as water flows between the gravel particles or sand grains. In SSF wetlands, roots may create preferential flow paths near the bottom of the wetland cell (Liehr *et al.*, 2000). In FWS wetlands, water near the surface is less subject to bottom drag and moves faster than the flow that is deeper in the water column. Water must detour around plant bases, which act as stagnant pockets that exchange water with adjacent flow channels by diffusion. Open water zones are subject to wind-driven mixing. The bottom topography may form deeper pathways, further contributing to short circuiting.

These combined phenomena produce a distribution of transit times for water parcels. The combined effect of these processes can be demonstrated by passing an inert tracer through the wetland. An impulse of the tracer, added across the flow width, moves with water through the wetland as a spreading cloud. Many treatment wetlands have been tracer tested, and all exhibit a significant departure from plug flow (Kadlec, 1994a; Stairs and Moore, 1994; King *et al.*, 1997). Figure B.2 displays the movement of a bromide tracer impulse through an aerated horizontal subsurface flow (HSSF) wetland, as inferred from a  $4 \times 4$  lateral and longitudinal array of sampling ports (Nivala, 2005). Similar two-dimensional profiles are shown in Figure 6.14 in Chapter 6.

Real-world flow patterns, such as the ones illustrated in Figure B.2, can be approximated using a variety of different flow models. The simplest, and most widely used, is to assume that the wetland can be represented as a series of CSTRs. This model, the TIS model, is addressed in the next section of this appendix.

#### THE TANKS-IN-SERIES FLOW MODEL

The TIS flow model bridges the gap between the idealized extremes of the PF and CSTR reactor types. In the TIS model, the wetland is represented by a number of CSTRs in series, as shown in Figure 6.19 in Chapter 6. The flow enters

#### Appendix B: Tracer Testing and Flow-Pattern Modeling



FIGURE B.1 Comparison of ideal reactors.

the first CSTR, is mixed, and then flows into the next CSTR. The number of tanks in the series, *N*, is an important parameter in the description of the movement of both reactive and nonreactive substances.

When N = 1, this TIS model simplifies to the CSTR ideal reactor. As the number of CSTRs increases, the flow comes closer to approximating plug flow (Crites and Tchobano-glous, 1998), as shown in Figure B.3. If there are an infinite number of tanks in series, the internal mixing goes to zero, and the TIS model simplifies to the ideal PF reactor. Thus, the tracer response curve generated by the TIS model is a function of *N*.

It is important to note that N is a mathematical fitting parameter. It does not represent the physical configuration of the wetland. A treatment wetland with three cells will not have N = 3.

#### TRACER VERSUS NOMINAL HYDRAULIC DETENTION TIMES

The number of tanks (N) that best represents the hydraulic characteristics of the wetland is not known *a priori*. If an impulse tracer test is conducted, the wetland will generate a tracer response curve at the outlet (or other monitoring location), similar to the ones shown in Figures 6.15–6.17, Chapter 6.

The tracer detention time,  $\tau$ , can be calculated from the tracer output data (Equation 6.36, Chapter 6):

$$\tau = \frac{1}{M_{o}} \int_{0}^{\infty} t Q C dt$$

Continuously-Stirred Tank Reactor (CSTR)



where

C(t) = tracer exit concentration, g/m<sup>3</sup> = mg/L  $M_{o}$  = mass of tracer in outflow, g  $\tau$  = tracer detention time, d t = time, d Q = average flow rate, m<sup>3</sup>/d

The tracer detention time,  $\tau$ , is often less than the nominal detention time  $\tau_n$ . This is because not all the wetland volume is involved in the flow path, as was assumed in the calculation of  $\tau_n$ . As discussed in Chapter 2, the volumetric efficiency,  $e_v$ , is an important parameter relating  $\tau$  and  $\tau_n$ . For FWS wetlands,  $e_v$  can be defined as follows (Equation 2.5):

$$e_{\rm V} = \frac{V_{\rm active}}{(LWh)_{\rm n}} = \frac{\varepsilon \eta h}{h_{\rm n}}$$

where

 $e_{\rm v}$  = wetland volumetric efficiency, dimensionless

 $V_{\text{active}} = \text{active wetland volume, m}^3$ 

- $\varepsilon$  = fraction of volume occupied by water, dimensionless
- $\eta$  = gross areal efficiency, dimensionless
- h = water depth, m
- $h_{\rm n}$  = nominal water depth, m
- $LWh_n$  = nominal wetland volume, m<sup>3</sup>

It is then clear that

$$\tau = e_{\rm V} \tau_{\rm n} \tag{B.10}$$

967



FIGURE B.2 Tracer movement in a HSSF wetland. Time-series tracer contours were plotted from influent/effluent data along with 18 internal sampling points using Groundwater Modeling System (GMS) software. During this study, the effluent tracer concentration was modeled as 6.2 TIS. (From Nivala et al. (2004) Hydraulic investigation of an aerated, subsurface flow constructed wetland in Anamosa, Iowa. Poster presentation at the 9th International Conference on Wetland Systems for Water Pollution Control, 26–30 September 2004, Association Scientifique et Technique pour l'Eau et l'Environnement (ASTEE), Cemagref, and IWA, Avignon, France.)

Table B.1 lists volumetric efficiency results from tracer testing efforts at the Orlando Easterly treatment wetland (Martinez and Wise, 2003b), where 15 of 17 FWS wetland cells were tracer tested.

#### THE DETENTION TIME DISTRIBUTION

Calculation of the tracer detention time,  $\tau$ , tells us a useful characteristic of the treatment wetland, namely, the average time water spends in the wetland. However, observation of tracer response curves, such as the ones shown in Figures 6.15–6.17, Chapter 6, clearly indicates that water is moving at different speeds within the wetland. Thus, the tracer response curve illustrates the entire range of detention times observed in the wetland. This range of detention times is termed as the *detention time distribution*, or DTD.

The DTD can be defined as

$$f(t)\Delta t$$
 = fraction of incoming water that stays in the  
wetland for a length of time between t and  $\Delta t$   
(B.11)

where

 $f = \text{DTD function}, d^{-1}$ t = time, d $\Delta t = \text{time increment}, d$ 

The exit tracer concentration is related to the DTD function. For an impulse tracer entering a system, the concentration curve, C(t), can be related to the DTD function, f(t), by

$$f(t) = \frac{QC(t)}{\int_{0}^{\infty} QC(t)dt}$$
(B.12)

where

C(t) = exit tracer concentration, g/m<sup>3</sup> = mg/L Q = water flow rate, m<sup>3</sup>/d

The numerator is the mass flow of the tracer in the wetland effluent at any time t after the time of the impulse addition. The denominator is the sum of all the tracer collected and thus should equal the total mass of tracer injected. Equation B.12 represents the observed DTD function.

If flow rate is constant, Q may be deleted from the numerator and denominator, and Equation B.12 simplifies to

$$f(t) = \frac{C(t)}{\int_0^\infty C(t)dt}$$
(B.13)

The tracer concentration can be measured at interior wetland points as well as at the outlet. Equation B.12 or B.13 may then be used to determine the distribution of transit times to that internal point. In this broader sense, the DTD becomes a function of internal position, f(x, t).

The TIS model described in Figure B.3 is defined as a number (*N*) of equally sized, perfectly mixed tanks arranged in series. The number of tanks can be any integral number between 1 and  $\infty$ . The response of this series of tanks is



**FIGURE B.3** Response of a closed vessel to a unit impulse of an ideal inert tracer as a function of the number of tanks in series. (Adapted from Levenspiel (1972) *Chemical Reaction Engineering*. First Edition, John Wiley and Sons, New York.)

|      |                   |                         | g at the of                        |                                     | liunus                        |
|------|-------------------|-------------------------|------------------------------------|-------------------------------------|-------------------------------|
| Cell | Cell Area<br>(ha) | Mass<br>Recovery<br>(%) | Actual Residence<br>Time<br>(days) | Nominal Residence<br>Time<br>(days) | Cell Volumetric<br>Efficiency |
| 1    | 23                | 109                     | 1.38                               | 4.53                                | 0.30                          |
| 2    | 25                | 123                     | 5.67                               | 6.47                                | 0.88                          |
| 3    | 6                 | 91                      | 1.34                               | 2.57                                | 0.52                          |
| 4    | 6                 | 95                      | 2.28                               | 8.97                                | 0.25                          |
| 5    | 6                 | 87                      | 0.44                               | 4.02                                | 0.11                          |
| 6    | 6                 | 84                      | 1.62                               | 2.29                                | 0.71                          |
| 7    | 12                | 97                      | 2.63                               | 13.00                               | 0.20                          |
| 8    | 12                | 112                     | 1.24                               | 2.95                                | 0.42                          |
| 9    | 11                | 101                     | 2.02                               | 6.74                                | 0.30                          |
| 10   | 11                | 111                     | 1.96                               | 3.44                                | 0.57                          |
| 11   | 23                | 105                     | 29.5                               | 60.5                                | 0.49                          |
| 12   | 24                | 105                     | 8.12                               | 11.7                                | 0.69                          |
| 13   | 52                | 75                      | 8.39                               | 20.8                                | 0.40                          |
| 14   | 47                | 92                      | 5.62                               | 12.3                                | 0.46                          |
| 15   | 54                | 94                      | 9.19                               | 12.5                                | 0.74                          |
|      |                   |                         |                                    |                                     |                               |

# TABLE B.1 Results of Cell-Wise Tracer Testing at the Orlando Easterly Wetlands

*Source:* Based on Martinez and Wise (2003b) *Journal of Environmental Engineering (ASCE)* 129(6): 553–560.

calculated from the dynamic tracer mass balance equations for the tanks:

$$V_j \frac{dC_j}{dt} = Q(C_{j-1} - C_j)$$
  $j = 1, 2, ..., N$  (B.14)

where

 $C_j$  = tracer concentration in unit *j*, mg/L = g/m<sup>3</sup> t = time, d  $V_j$  = volume of unit *j*, m<sup>3</sup>

Equation B.14 is easily rearranged:

$$\tau_j \frac{dC_j}{dt} + C_j = C_{j-1}$$
  $j = 1, 2, ..., N$  (B.15)

where

 $\tau_i$  = tracer detention time in unit *j*, d

Because all the units are of equal volume, the tracer detention time of the entire system is  $\tau = N\tau_j$ . If a unit impulse of concentration is fed to the series of tanks as a feed concentration condition, the resulting effluent concentration from the *Nth* tank is the tracer concentration response according to the model. Thus, Levenspiel (1972) demonstrates that the DTD curve for the TIS model can be represented by

$$f(t) = \frac{N^N t^{N-1}}{\tau^N (N-1)!} \exp\left(\frac{-Nt}{\tau}\right)$$
(B.16)

#### **MOMENT ANALYSIS**

The moments of the DTD define the key parameters that characterize the wetland, the two most important being the actual detention time and spreading of the concentration pulse due to mixing (variance of the pulse). The *nth* moment about the origin is defined by

$$M_{\rm n} = \int_0^\infty t^{\rm n} f(t) dt \tag{B.17}$$

The zeroth moment represents the definition of the fractional character of the DTD function. Because the term  $f(t)\Delta t$  represents the fraction of tracer that spends between time t and  $t + \Delta t$  in the system, the sum of these fractions is unity:

$$\int_{0}^{\infty} f(t)dt = 1$$
 (B.18)

The first absolute moment is the tracer detention time  $\tau$ . This value defines the centroid of the exit tracer concentration distribution:

$$\int_{0}^{\infty} t f(t) dt = \tau$$
 (B.19)

It is sometimes useful to work with a dimensionless time variable, defined as the actual time divided by the tracer detention time:

$$\theta = \frac{t}{\tau} \tag{B.20}$$

A second parameter that can be determined directly from the residence time distribution is the variance ( $\sigma^2$ ), which characterizes the spread of the tracer response curve about the mean of the distribution, which is  $\sigma^2$ . This is the second central moment about the mean:

$$\int_0^\infty (t-\tau)^2 f(t) dt = \sigma^2$$
 (B.21)

where

 $\sigma^2 = DTD$  variance,  $d^2$ 

The variance of the DTD is created by the mixing of water during passage, or, equivalently, by a distribution of the velocities of passage. This can be lateral, longitudinal, or vertical mixing. This measure of dispersive processes may be rendered dimensionless by dividing by the square of the tracer detention time:

$$\sigma_{\theta}^2 = \frac{\sigma^2}{\tau^2} \tag{B.22}$$

The new parameter is  $\,\sigma_{\theta}^2\,,$  the dimensionless variance of the tracer pulse.

For the TIS model, it is possible to define simple relations between the parameters of the distribution and these moments. For instance, the TIS conceptual model (which produces a gamma distribution) has a dimensionless variance, given by

$$\sigma_{\theta}^2 = \frac{\tau - \tau_p}{\tau} \tag{B.23}$$

$$\sigma_{\theta}^2 = \frac{1}{N} \tag{B.24}$$

#### **GAMMA DISTRIBUTION FITTING**

Virtually the entire early literature on tracer testing of wetlands and ponds utilized (archaic) parameter estimation methods that reflected the computational tools available when they were developed around 35 years ago. The most common method involves computation of the first and second moments of the experimental outlet concentration distribution (Equations B.19 and B.21) via numerical integration.

# TABLE B.2Sample Calculations for Workup of a Tracer Test

| Background = 9 μg/L<br>Tracer Added = 782 kg<br>Recovery = 98% |                |                                | τ = 12.95 d<br>σ2 = 61.15 d2<br>σ2θ = 0.365 |              |                                | Moment<br>N = 2.74<br>$t_j = 4.722 \text{ d}$<br>$\tau = 12.95 \text{ d}$ |                         |                                 |                       |                    |  |
|--|----------------|--------------------------------|---|--------------|--------------------------------|---|-------------------------|---------------------------------|-----------------------|--------------------|--|
|  |                | David                          | A directo d                                 |              |                                |   |                         | Moment                          |                       |                    |  |
| Elapsed Time<br>(days)   | Flow<br>(m³/d) | Kaw<br>Concentration<br>(µg/L) | Concentration<br>(µg/L)                     | QC∆t<br>(kg) | Data DTD<br>(d <sup>-1</sup> ) | tQC∆t   | $(t-\tau)^2 tQ\Delta t$ | Gamma DTD<br>(d <sup>-1</sup> ) | Pred. Conc.<br>(µg/L) | Gamma<br>DTD (1/d) |  |
| 0.0  | 275,558        | 9                              | 0   |              | 0.000                          |   |                         | 0.000                           | 9                     | 0.000              |  |
| 0.9  | 275,558        | 9                              | 0   | 0            | 0.000                          | 0   | 0                       | 0.000                           | 9                     | 0.000              |  |
| 1.2  | 284,672        | 8                              | -1  | 0            | 0.000                          | 0   | -6                      | 0.006                           | 9                     | 0.000              |  |
| 1.5  | 284,672        | 9                              | 0   | 0            | 0.000                          | 0   | -3                      | 0.009                           | 9                     | 0.001              |  |
|  |                |                                |   |              |                                |   |                         |                                 |                       |                    |  |
| 3.9  | 278,499        | 44                             | 35  | 3            | 0.013                          | 12  | 288                     | 0.038                           | 91                    | 0.025              |  |
| 4.2  | 263,747        | 109                            | 100   | 6            | 0.034                          | 25  | 471                     | 0.041                           | 103                   | 0.031              |  |
| 4.5  | 263,747        | 100                            | 91  | 8            | 0.031                          | 36  | 620                     | 0.044                           | 113                   | 0.037              |  |
| 4.9  | 263,747        | 191                            | 182   | 12           | 0.062                          | 57  | 808                     | 0.047                           | 129                   | 0.044              |  |
|  |                |                                |   |              |                                |   |                         |                                 |                       |                    |  |
| 2.6  | 223,775        | 20                             | 11  | 5            | 0.003                          | 161   | 1,776                   | 0.005                           | 35                    | 0.000              |  |
| 5.6  | 143,877        | 14                             | 5   | 5            | 0.001                          | 161   | 1,998                   | 0.004                           | 29                    | 0.000              |  |
| 7.6  | 260,816        | 13                             | 4   | 2            | 0.001                          | 65  | 1,008                   | 0.002                           | 27                    | 0.000              |  |
| 9.6  | 298,678        | 16                             | 7   | 3            | 0.003                          | 124   | 2,144                   | 0.002                           | 30                    | 0.000              |  |
| 2.6  | 596,050        | 16                             | 7   | 10           | 0.005                          | 396   | 7,838                   | 0.001                           | 16                    | 0.000              |  |
| 4.6  | 507,213        | 14                             | 5   | 6            | 0.003                          | 280   | 5,991                   | 0.001                           | 13                    | 0.000              |  |
| 6.6  | 234,219        | 14                             | 5   | 4            | 0.001                          | 160   | 3,696                   | 0.001                           | 11                    | 0.000              |  |
| bum or average   | 276,069        |                                |   | 769          |                                | 9,953   | 46,990                  |                                 |                       |                    |  |

A serious failing of the moment method of parameter estimation is that it emphasizes the "tail" of the response much more than the central portion—i.e., the peak area. Minor concentration anomalies on the tail of the concentration response curve may yield spurious parameter values. Often, a better procedure is to utilize a robust parameter determination routine, such as a search to minimize the sum of the squared errors between the selected DTD function and the data.

From Figure B.3, it is easy to see that the shape of the DTD is quite sensitive to changes in N when N is small. Note the change in magnitude and shape as the number of tanks increases from the ideal CSTR (N = 1) to 2 TIS and from 2 to 6 TIS. Because most wetland systems operate as a few (3–8) TIS, it is advantageous to be able to change N from a discrete integer variable to a continuous (noninteger) variable. This enables the modeler to utilize fractional values of N, increasing the flexibility with which a dataset can be fit with a model. The gamma distribution f(t) is defined as:

$$f(t) = \frac{N^{N} t^{N-1}}{\tau^{N} \Gamma(N)} \exp\left(\frac{-Nt}{\tau}\right)$$
(B.25)

The gamma function  $\Gamma(N)$  is defined by

$$\Gamma(N) = \int_0^\infty \exp(-x) x^{N-1} dx \qquad (B.26)$$

Equation B.25 represents a DTD function that may be fit to data. The GAMMADIST function is available in Microsoft Excel<sup>TM</sup> and returns values of *f* for the time *t* and the parameters *N* and  $\tau$ .

The SOLVER application in Microsoft Excel<sup>TM</sup> allows the modeler to simultaneously solve for the variables Nand  $\tau$  that minimize the difference between the observed DTD (Equation B.13) and the predicted DTD (Equation B.25). Examples of results of this approach are shown in Figures 6.13 and 6.15, Chapter 6.

As an illustration of the potential problems of the old moment analysis procedure and the ability of the sum of the squared errors (SSQE) minimization, consider the data set for the lithium tracer test of Cell 2 of the Everglades Nutrient Removal Project, Florida, FWS wetland (Figure B.4). Computations are illustrated in Table B.2. SSQE fits the peak area of the response, whereas moment calculations fit the tail. Moment analysis produces a higher tracer detention time (12.95 days versus 11.17 days) and a lower number of TIS (2.74 versus 5.47). The moment parameters produce a poorly appearing "fitted" gamma curve. The bulk of the tracer, and hence the important part of the response, is contained in the peak zone. Accordingly, the SSQE minimization analysis of tracer data is recommended, rather than moment calculations.

Here, the goodness of fit is measured via the root mean square (RMS) error between model and data DTD values. The range  $0 < \theta < 4$  is chosen to eliminate repeated zero errors associated with the tail of the distribution. The RMS

error is divided by the peak height of the distribution to provide shape scaling. The RMS error for the moment fit in Figure B.4 is 24.5%, whereas the SSQE fit yields an RMS error of 9.2%.

#### TRACER TEST OBSERVATIONS

Treatment wetlands have been built to many different specifications and in many geometric layouts. Tracer tests for many have produced similar results, without evidence of pathological hydraulic behavior. Here, examples are given to illustrate commonly encountered features.

### FWS WETLAND SYSTEMS

The results of an illustrative set of tracer test results for FWS wetlands is given in Table 6.1, Chapter 6. The average recovery for those 35 systems was 84%, the mean NTIS = 4.1, and the median NTIS = 3.6. More detailed information for a FWS system is informative.

The Tres Rios, Arizona, demonstration project conducted over 20 tracer tests of FWS wetlands used to polish municipal effluent. The Tres Rios Demonstration Constructed Wetland Project consisted of three discrete sites totaling 5.8 ha, of which 4.3 ha comprised two demonstration-scale free water surface (FWS) wetland facilities: a hayfield riparian site (H1 and H2) and a cobble site (C1 and C2). Wetland H2 was a 1.28-ha with a typical detention time of four days. Basin H2 had approximately 25% of its surface area as open-water deep zones, obtained using two large internal deep-zones with waterfowl islands. The primary vegetation consisted of two species of bulrush, *Scirpus validus* (soft-stem bulrush) and *Scirpus olneyi* (three-square bulrush). Tracer results have been discussed in Whitmer *et al.* (2000) and Keefe *et al.* (2004b).

The data from one of the bromide impulse tests are shown in Figure B.5, and the conditions for the test are given in Table B.3. The nominal detention time was 75 hours. A typical bell-shaped response is seen, with the first tracer appearing at the outlet at 16 hours. The tracer recovery was 88%, which indicates relatively conservative behavior. Three methods of analysis are illustrated: TIS from moments, TIS from least squares, and delayed (shifted) TIS from least squares. The RMS goodness of fit improves in that order (Table B.3). Depending on the fitting technique, the volumetric efficiency ranges 71-76%, indicating that most of the wetland water is involved in flow. The dimensionless variance is 0.237, corresponding to overall TIS = 4.2. However, if the shifted TIS DTD was used, the wetland behaved similar to a plug flow unit of 16 hours detention, combined with 38 hours detention in 2.8 TIS. The TIS moment fit of the DTD appears good only for the tail of the DTD.

The conversions for first-order, zero-background removal are given in Table B.3. In general, the plug flow approximation is not good, except for very low removals (Da = 1).



**FIGURE B.4** Tracer response for Cell 2 of the ENRP project, together with the least squares fit to a gamma function. The lower panels display expansions of the starting and ending periods of the test.

#### **HSSF WETLAND SYSTEMS**

The results of an illustrative set of tracer test results for HSSF wetlands are given in Table 6.2, Chapter 6. The average recovery for the 37 systems was 92%, the mean NTIS = 11.0, and the median NTIS = 8.3. More detailed information for a HSSF system is informative.

The HSSF wetland system at Minoa, New York, consisted of three flow paths with two cells in series in each, totaling 0.67 ha. The average design flow was 600 m<sup>3</sup>/d, corresponding to a nominal detention time of three days. The substrate was 10–15 cm of 6-mm pea gravel on top of 75 cm of 20 mm gravel, and the cells were vegetated with *Phragmites australis* and *Scirpus validus*. Tracer results have been discussed in Marsteiner *et al.* (1996) and Marsteiner (1997). For the test example, the full flow was directed to cell 1.

The data from one of the bromide impulse tests are shown in Figure B.6, and the conditions for the test are given in Table B.3. The nominal detention time was 20.6 hours. A typical bell-shaped response is seen, with the first tracer appearing at the outlet at 9.6 hours. The tracer recovery was 98%, which indicates conservative behavior. Three methods of analysis are illustrated: TIS from moments, TIS from least squares, and delayed (shifted) TIS from least squares. The RMS goodness of fit improves in that order (Table B.3). Depending on the fitting technique, the volumetric efficiency ranges from 75–79%, indicating that most of the wetland water is involved in the flow. The dimensionless variance is 0.089, corresponding to overall TIS = 11.2. However, if the shifted TIS DTD was used, the wetland behaved similar to a plug flow unit of 9.6 hours' detention, combined with 11 hours' detention in 6.9 TIS. The TIS moment fit of the DTD appears good.

The conversions for first-order, zero-background removal are given in Table B.3. In general, the plug flow approximation is not good, except for very low removals (Da = 1).

### **EVENT-DRIVEN WETLAND SYSTEMS**

Tracer analysis of event-driven systems is complicated by two factors: the flow is not steady, and all the tracer may not be flushed out of the wetland by a single event. Despite these difficulties, it has been shown that the hydraulic flow patterns are similar under event-driven and continuous flow (Werner and



FIGURE B.5 FWS tracer test results for Tres Rios Hayfield wetland 2, together with three different TIS fits. Conditions are given in Table B.3.

Kadlec, 1996). Methods for dealing with unsteady flows and depths have been outlined by Holland *et al.* (2004; 2005).

nates before flushing the wetland. A nominal detention time of three days is selected, corresponding to a fixed inflow of 500 m<sup>3</sup>/d and a full-flow volume of 1,500 m<sup>3</sup>. During the tracer test, the wetland receives 500 m<sup>3</sup>/d for a period of three

It is instructive to examine the hypothetical response of a 4-TIS wetland to a tracer addition to an inflow that termi-

#### **TABLE B.3**

Hayfield 2 FWS

# Details of Tracer Tests for the Tres Rios Hayfield, Arizona (FWS), and Minoa, New York (HSSF), Examples

|                            | 74.4   |               |                       |           |
|----------------------------|--------|---------------|-----------------------|-----------|
| Nominal detention time (n) | /4.6   |               |                       |           |
| % Recovery                 | 88%    |               |                       |           |
| Dimensionless variance     | 0.237  |               |                       |           |
|                            | Moment | Least Squares | Shifted Least Squares | Plug Flow |
| Tracer detention time (h)  | 56.4   | 53.0          | 53.5                  | _         |
| Volumetric efficiency, %   | 76%    | 71%           | 72%                   | _         |
| Plug flow fraction, %      | 0      | 0             | 30%                   | _         |
| Number of TIS              | 4.2    | 6.2           | 2.8                   | _         |
| RMS goodness of fit, %     | 15.9   | 6.6           | 3.4                   | _         |
| Remaining @ Da = 1, %      | 40.8%  | 39.6%         | 39.7%                 | 36.8%     |
| Remaining @ Da = 3, %      | 10.4%  | 8.7%          | 8.5%                  | 5.0%      |
| Remaining @ Da = 5, %      | 3.7%   | 2.6%          | 2.3%                  | 0.7%      |
| Minoa HSSF Cell 1          |        |               |                       |           |
| Nominal detention time (h) | 20.4   |               |                       |           |
| % Recovery                 | 98     |               |                       |           |
| Dimensionless variance     | 0.089  |               |                       |           |
|                            | Moment | Least Squares | Shifted Least Squares | Plug Flow |
| Tracer detention time (h)  | 16.1   | 15.4          | 16.0                  | _         |
| Volumetric efficiency, %   | 79%    | 75%           | 78%                   | —         |
| Plug flow fraction, %      | 0      | 0             | 47%                   | —         |
| Number of TIS              | 11.2   | 14.3          | 3.7                   | _         |
| RMS Goodness of Fit, %     | 13.3   | 9.6           | 6.9                   | —         |
| Remaining @ Da = 1, %      | 38.4%  | 38.0%         | 38.1%                 | 36.8%     |
| Remaining @ Da = 3, %      | 7.0%   | 6.6%          | 6.5%                  | 5.0%      |
| Remaining @ Da = 5, %      | 1.6%   | 1.4%          | 1.3%                  | 0.7%      |
|                            |        |               |                       |           |



**FIGURE B.6** Tracer test results for a HSSF wetland at Minoa, New York, together with three different TIS fits. Conditions are given in Table B.3.

days, but then the inflow stops. It is presumed that the wetland outflow is governed by a weir structure. The tracer concentration response at the system outlet is shown in Figure B.7. Two artifacts of the test results are apparent. First, there is a delay as the water level builds up in the wetland, with low outflows as the height over the weir increases. If there were no outflow, it would take three days to fill the wetland to the new depth. After the inflow ceases, the wetland drains back down to the elevation of the weir. Outflows decrease back down to zero over the next few days. There is residual tracer in the wetland, corresponding to a recovery of 68% (32% remaining). As a second result, the concentration near the outflow point, which has become stagnant, remains at an elevated value until another event again causes outflow.

Such distortion of the DTD makes it difficult to ascertain the hydraulic parameters of the wetland. A flow-weighted time, proportional to the volume of water that has exited the wetland, removes these two artifacts. On that basis, the response changes to the shape characteristic of continuous flow systems. There are alternative choices for scaling, as discussed by Werner and Kadlec (1996), who provide the mathematical background for rescaling to the volumetric approach.

#### VARIABILITY IN TRACER RESULTS

As for any other treatment wetland performance parameter, there is variability in the volumetric and DTD efficiency results. That variability may be caused by seasonal variables, such as litter or algal density; or it may be caused by meteorological factors, such as wind, evapotranspiration (*ET*), or rainfall. A set of six warm-season tests on FWS wetland EW3 at Des Plaines, Illinois, gave  $e_V = 0.70 \pm 0.13$  and  $e_{DTD} = 0.62 \pm 0.10$  (Kadlec, 1994). Results from the Tres Rios, Arizona, demonstration wetlands (N = 3) showed a narrower range for  $e_{DTD}$ , with a typical coefficient of variation of 0.03–0.06.



**FIGURE B.7** Tracer response for a hypothetical stormwater wetland. The inflow is presumed to last for three days (a), during which the system fills to a new operating depth. The tracer is not completely flushed (b), resulting in a residual concentration. The solid line shows a rescaling of "time" to a cumulative volume outflow basis.



**FIGURE B.8** (A color version of this figure follows page 550) Progress of Rhodamine WT dye tracer through a FWS wetland, cell 4 of the ENRP in Florida. The dye was introduced along the upper boundary, and flow proceeds from the top to the bottom. Note the short-circuit along the left-hand side, which is partially redistributed by the central cross canal. (Photo courtesy T. DeBusk.)

However, there was wider variability for  $e_v$ , with a typical coefficient of variation of 0.13–0.33. Thus, it appears that the coefficient of variation for efficiency results may be in the range 5–30% for FWS systems.

# **COMMON ABERRATIONS**

Although it is tempting to think that the entire wetland water volume is swept by the flow in a moderately uniform manner giving rise to a gamma DTD, deviations from that pattern are commonly found. Two pathological situations are the existence of short-circuits from inlet to outlet and the existence of deadwater zones that are not swept by flow.

#### SHORT-CIRCUITING

When part of the water follows a fast, preferential path through the wetland, the result is termed channeling or short-circuiting. On the ground, these fast flow paths may result from bathymetry, such as deeper channels from inlet to outlet (see Figure B.8). The tracer detention time will be less than the nominal. A pathological case is illustrated in Figure B.9, Lakeland, Florida, cell 1 (Keller and Bays, 2001). The recovery was 106%. The nominal detention time was 17.3 days; the tracer detention time was 5.8 days, for a volumetric efficiency of 33%. The dimensionless variance was 0.66, corresponding to *N*TIS = 1.5. The DTD curve for this wetland was clearly bimodal, indicating two flow paths. When the DTD is fit with a two-path



FIGURE B.9 Tracer response for a short-circuited FWS wetland, Cell 1 at Lakeland, Florida.

model, the fit is excellent (see section titled Other Flow Models). About a third of the water had a mean detention time of 1.6 days, whereas the remaining two thirds had a mean detention time of 7.9 days. Cell 1 contained large internal areas of linear spoil mounds parallel to the direction of flow and, therefore, presumably, was highly channelized between these areas.

#### DEAD ZONES

Wetlands often contain parcels of water that are not in the main flow path and are not flushed by flowing water. Such zones may be due to water trapped in a mass of algae or a dense clump of vegetation or litter in the FWS wetland. In a HSSF wetland, there may be dead-end pores. Tracer enters and departs these zones by diffusion, which is usually a slow process compared to flow. As a consequence, the tracer response will exhibit a long tail corresponding to the tracer that parked temporarily in the dead zones. An example from Sacramento, California, is shown in Figure B.10, along with a TIS fit (Nolte and Associates, 1998b). The nominal detention time for this test was 5.5 days, the tracer detention time was 5.3 days, and the recovery was 97%. If the moment method is used to fit the data, the tail region controls, and the peak zone is poorly represented. Alternative methods of analysis are discussed in the section on wetland-tracer interactions that can account for the dead zones, but at the expense of additional modeling parameters. The implications for pollutant removal are discussed in the section on pollutant removal effects.

# EXTENSIONS TO THE TIS FLOW MODEL

The simplest TIS model, and the gamma distribution that represents it, does not allow for some of the very real phenomena that may be encountered. DTD may result from velocity profile effects rather than mixing. When that is the case, it has a zero portion for short times, up to the shortest travel time experienced by rapidly moving water. For instance, that rapid path is typically associated with surface water layers in unvegetated areas of a FWS wetland. In HSSF wetlands, the rapid paths are the most direct routes between the media particles, as opposed to paths that wander off to the side to move around particles. In either case, there is a nonzero minimum of the travel time. This concept is discussed in detail in the engineering literature (see for example, Levenspiel, 1972). Another set of unaccounted processes includes water gains and losses, in the form of seepage, rainfall, and evaporation. These factors may be included by modifying the TIS model structure.

#### TIS PLUS A DELAY

The TIS model has been described earlier (in the section on the TIS flow model) as an example of the use of least squares fitting of DTDs. As noted, it is a two-parameter fit, using detention time  $\tau$ , and number of tanks *N*. It does not suffer from a constraint of small degrees of nonideality and can cover the entire range from one well-mixed unit to a plug flow. Drawbacks are the inability to describe either the breakthrough delay or long tail resulting from retardation.

The tanks plus a delay have been utilized as a model for dealing with the breakthrough delay evidenced in most tracer response curves. This model may also be easily coded in a spreadsheet, but there are three parameters: the delay time  $t_D$ , the detention time  $\tau$ , and the number of tanks *N*. Many authors recommend the inclusion of this component of the response (Kadlec *et al.*, 1993; Kadlec and Knight, 1996; Chazarenc *et al.*, 2004; Marsili-Libelli and Checchi, 2005).



**FIGURE B.10** Tracer test result from the Sacramento, California, wetland Cell 7. The least squares TIS model does not account for the long tail of the experimental curve. The moment method fits the tail, but misses the peak area. (Data from Nolte and Associates (1998a) *Sacramento Regional Wastewater Treatment Plant Demonstration Wetlands Project*. 1997 Annual Report to Sacramento Regional County Sanitation District, Nolte and Associates.)

$$f(t) \begin{cases} = \frac{1}{t_i (N-1)!} \left(\frac{t-t_{\rm D}}{t_i}\right)^{N-1} e^{\left(\frac{-t-t_{\rm D}}{t_i}\right)} & t > t_{\rm D} \\ = 0 & t < t_{\rm D} \end{cases}$$
(B.27)

where

t = detention time, d

 $t_{\rm D}$  = delay time, d

 $t_i$  = mean detention time in one tank, d

#### INFILTRATION

Some wetlands may safely infiltrate water into the ground. For example, the Tres Rios, Arizona, cobble site wetland, C1, infiltrated 60–80% of the incoming water (Kadlec, 2001c). Similarly, the Imperial, California, wetlands also leaked a considerable fraction of the incoming water, 40–60% (TTI and WMS, 2006). The tracer test theory does not usually include this leak effect on the water mass balance.

For illustration, let the model framework be the TIS concept discussed previously. The volume, depth, and planar area are considered to be the same for each unit. The leak rate is also assumed to be the same in each unit. For simplicity, the effects of rain and ET will be omitted from this analysis. The steady-flow water mass balance equation for the *jth* well-mixed unit is

$$Q_{j-1} = Q_j + L$$
  $j = 1, 2, ..., N$  (B.28)

where

 $L = \text{leak from unit } j, m^3/d$ 

N = total number of units in the TIS model, integer

 $Q_i$  = overland flow from unit *j*, m<sup>3</sup>/d

Leakage acts to reduce the flow as water moves from inlet to outlet. Equation B.28 may be solved sequentially to determine the flow exiting each unit:

$$Q_i = Q_i - jL$$
  $j = 1, 2, ..., N$  (B.29)

where

 $Q_{\rm i}$  = inlet flow rate, m<sup>3</sup>/d

The total leakage is

$$NL = \alpha Q_{\rm i}$$
 (B.30)

where

 $\alpha$  = total fraction of inlet flow that is lost through leakage, dimensionless

At constant water volume in each unit, the tracer mass balances are

$$V_j \frac{dC_j}{dt} = Q_{j-1}C_{j-1} - (Q_j + L)C_j$$
  $j = 1, 2, ..., N$  (B.31)

where

$$C_j$$
 = tracer concentration in unit *j*, mg/L = g/m<sup>3</sup>  
t = time, d  
 $V_i$  = volume of unit *j*, m<sup>3</sup>

Equations B.28 and B.31 combine to give

$$\tau_j \frac{dC_j}{dt} + C_j = C_{j-1}$$
  $j = 1, 2, ..., N$  (B.32)

where

$$\tau_j = \frac{\tau_{in}}{\left[N - \alpha(j-1)\right]}$$
  $j = 1, 2, ..., N$  (B.33)

The individual unit detention times  $\tau_j$  are based on the combination of surface flow and leakage leaving the *jth* unit and its water volume. The nominal system detention time based on inlet flow  $Q_i$  and the total system water volume is

$$\tau_{\rm in} = \frac{NV}{Q_{\rm i}} \tag{B.34}$$

If there is no leakage, then  $\alpha = 0$ , and  $\tau_i = \tau_{in}/N$ .

$$\tau_{\rm an} = \tau_{\rm in} \left( \sum_{j=1}^{N} \frac{1}{N - \alpha(j-1)} \right) \tag{B.35}$$

where

 $\alpha$  = water loss fraction, dimensionless

$$(\alpha = 1 - R = 1 - Q_{o}/Q_{i})$$

j = tank number counter, dimensionless

N =total number of tanks, integer

 $\tau_{an}$  = actual nominal detention time, d

 $\tau_{in}$  = flow-based inlet nominal detention time, d

The effect of leakage on the measured detention time can be quite large for high values of  $\alpha$ , especially for high values of *N*TIS (Figure B.11). For example, if half the incoming water is lost, the true detention time for a 3-TIS wetland will be 23% greater than the inlet nominal detention time. The use of an average flow rate will always give an overestimate of the actual detention time.

The tracer is lost to leakage, and so the recovery will be less than 100%. The lowered surface outflow leads to a low and late peak (Figure B.12). However, the shape of the response is not affected, and hence the analysis of the response will give the same dimensionless variance (same number of TIS).

#### **R**AIN AND **EVAPOTRANSPIRATION**

The loss or gain of water to or from the atmosphere does not carry tracer in or out of the wetland. However, *ET* does cause the water to slow as it passes through the system, and rain causes it to accelerate. Because there is normally level control at the outlet, the depth remains unchanged, but the linear



**FIGURE B.11** Detention times in leaking wetland systems, expressed as a ratio to the nominal detention time, computed from the inlet flow rate. The fractional water loss is the total for the entire wetland.

velocity of the remaining water is altered. Accordingly, for *ET*, the detention time is increased (see Chapter 2), and dissolved constituents become more concentrated. Conversely, for rain, the detention time is decreased, and dissolved constituents become diluted. The effects on tracer response have been discussed by Chazarenc *et al.* (2003; 2004), who present the theoretical result for detention time in plug flow systems with *ET* (Chapter 2, Equation 2.8):

$$\tau_{\rm an} = \tau_{\rm in} \left( \frac{\ln(R)}{R-1} \right)$$

where

R = water recovery fraction, dimensionless ( $R = Q_0/Q_1$ )

 $\tau_{an}$  = actual nominal detention time, d

 $\tau_{in}$  = flow-based inlet nominal detention time, d

This plug flow formula works equally well for rainfall gains. However, this is not the case for a TIS system, in which the influence of precipitation and ET is greater. The actual detention time (tracer detention time) in a TIS wetland is

$$\tau_{\rm an} = \tau_{\rm in} \left( \frac{1}{N} \sum_{j=1}^{N} \left( \frac{1}{1 - \frac{\alpha_j j}{N}} \right) \right) \tag{B.36}$$

where

 $\alpha$  = water loss fraction, dimensionless ( $\alpha = 1 - R = 1 - Q_0/Q_i$ )

j = tank number counter, dimensionless

N =total number of tanks, integer

In the limit, as *N* becomes very large, Equation B.36 reduces to Equation B.35.



**FIGURE B.12** The effect of leakage on a tracer response for 4 TIS. The line is the forecast result for no leakage loss. The circles represent the result for 50% water loss due to leakage.



**FIGURE B.13** Detention times in wetland systems with rain or evapotranspiration, expressed as a ratio to the nominal detention time computed from the inlet flow rate. The fractional water loss or gain is the total for the entire wetland.

The effect of ET on the measured detention time can be quite large for high values of  $\alpha$ , especially for low *N*TIS (Figure B.13). For example, if half the incoming water is lost, the true detention time for a 3-TIS wetland will be 57% greater than the inlet nominal detention time. The use of an average flow rate will always give an underestimate of the actual detention time for *ET* and an underestimate for rain cases. The error is large for relatively large amounts of *ET*.

None of the tracer is lost to ET, so the theoretical recovery should be 100%. The combination of the evaporative concentration and lowered outflow leads to a high and late peak (Figure B.14). The combination of rain dilution and increased outflow leads to a low and early peak. However, the shape of the response is not affected, and hence the analysis of the response will give the same dimensionless variance (the same number of TIS).

# WETLAND-TRACER INTERACTIONS

In the foregoing, it has been assumed that the wetland water body can be considered as vertically uniform and that the tracer does not interact with any of the solids or biota in the system. In some cases, these assumptions are not warranted.

#### WIND

If the wetland contains significant areas of open water, wind can be a factor in tracer movement. In ponds, field studies with drogues and computational fluid dynamics (CFD) modeling (HYDRO-3D) have shown that surface velocities may be 30-fold greater than deep-layer velocities and that the velocity profile is most affected in the top 10–15 cm (Guganessharajah, 2001). Lloyd *et al.* (2003) implemented windbreaks around a shallow pond (1.1 m deep), thus isolating the system from



**FIGURE B.14** The effects of *ET* and rain on a tracer response for 4 TIS. The line is the forecast result for no *ET* loss. The open circles represent the result for 50% water loss due to *ET*. The closed circles represent the result for 50% water gain from rain.

winds that averaged only 0.8 m/s. The volumetric efficiency was increased from 50% to 74%, and the dispersion number was decreased from 0.66 to 0.40.

In laboratory flume experiments, with wooden dowels representing plants, Stephan *et al.* (2004) showed that tracer response curves differed in shape depending on whether the wind was with or against the flow. Wind acting on surface layers drives a surface current in the wind direction and promotes vertical mixing via recirculation in the water column. Therefore, Stephan *et al.* (2004) found that the tail of the response curve was shortened for a wind of 2.4 m/s blowing against the flow direction. The volumetric efficiency was higher with the tail wind (83%) than with the head wind (74%).

Stairs (1993) found that a tail wind of 5.7 m/s caused a very early peak concentration in the response compared to more quiescent conditions for an unvegetated FWS wetland.

There are no sufficient experimental results on vegetated operating FWS systems to formulate quantitative measures of wind effects at this point in time.

#### ICE

Tracer tests for frozen conditions were conducted by Smith *et al.* (2005), who concluded that flow conditions "appeared to be good in both ice-covered and unfrozen conditions." The shapes of the tracer responses were very similar, and the volumetric efficiencies were nearly the same, for ice-free and under ice conditions.

#### **D**EGRADATION AND LOSS

Recovery of tracer is an extremely important quality check for the measured DTD. Failure to recover 100% of the tracer may mean that the tracer adsorbed or was degraded during passage through the wetland. Organic compounds, including the fluorimetric dyes often used for water tracing in mineral systems, are notorious in this respect: they disappear in wetlands. Noninteractive, inorganic substances are to be preferred, lithium ions and bromide ions being two of the more popular ones. Batch microcosm tests can help to establish the degree of interaction between a specific tracer and the wetland in question. Interactive, disappearing tracers produce serious errors in the inferred mixing parameters.

The use of a sorbing tracer can distort the tracer response curve and lead to errors in calculating hydraulic characteristics. An irreversibly sorbing tracer such as rhodamine WT may cause the peak time to be shorter than it really is, whereas a reversibly sorbing tracer will cause a flattening of the DTD and an unrepresentative extension of the tail. Dierberg and DeBusk (2005) reported that the recovery of rhodamine WT declined as the initial concentration of the impulse was reduced.

It is possible that molecular tracers may degrade during travel through the wetland. This is especially true for the organic dyes, such as rhodamine. These may be subject to photolytic decomposition, or to the action of microbes that use the tracer as a carbon source. Irreversible sorption has the same effect, because it removes the tracer from the water, with no chance of return. Additionally, it is possible that the tracer is permanently removed by plant uptake, at least on the time scale of a tracer test. Although such losses cannot be entirely prevented, it is possible to assess its potential effects on the results of the test.

We begin by supposing that the removal is first-order and apportioned equally in all portions of the water column. Therefore, each parcel of water traversing the wetland will lose tracer exponentially with respect to its travel time. We also suppose that the DTD is given by a gamma function, according to Equation B.25. If the rate coefficient is k, then the fractional concentration of the tracer exiting with a given parcel between time = t and time = t + dt is

$$\frac{C(t)}{C_{\rm i}} = g(t)e^{-kt} = \frac{1}{t_i \,\Gamma(N)} \left(\frac{t}{t_i}\right)^{N-1} e^{\left(-t/t_i\right)} e^{-kt} \quad (B.37)$$

where

C = tracer outlet concentration, mg/L

 $C_i$  = tracer inlet concentration, mg/L

k = tracer loss rate coefficient, 1/d

t = detention time, d

 $t_i$  = mean detention time in one tank, d

N = number of tanks

This equation is still a gamma distribution with the same N as that for the nondestructive case. However, the detention time  $(t = Nt_i)$  has been shortened:

$$\tau_{app} = N \frac{t_i}{1 + kt_i} = \frac{\tau_{act}}{1 + k \frac{\tau_{act}}{N}}$$
(B.38)

where

 $\tau_{act}$  = actual detention time, d  $\tau_{app}$  = apparent detention time, d

Because the apparent detention time has been shortened, the volumetric efficiency will appear to be reduced accordingly. However, the number of TIS is not affected. If the distribution of Equation B.25 is averaged over all parcels, the mass recovery of tracer is given by

Fraction recovery = 
$$\left(1 - k \frac{\tau_{app}}{N}\right)^N$$
 (B.39)

An example of the effect of tracer loss is given in Figure B.15. This effect is illustrated in the work of Bowmer (1987).

#### RETARDATION

The tracer may also be retained in the wetland, but not lost. This can occur because of the presence of dead zones, either large or small scale, that gain the tracer by diffusion, retain it until the pulse has passed, and then release it back to the flowing water. Reversible sorption on any of several wetland solids can lead to the same phenomenon. Tracer is sorbed on



**FIGURE B.15** The effect of tracer loss on the DTD for a wetland with N = 4. The actual detention time was ten days, the measured tracer detention was 8.4 days, and the mass loss of tracer was 50%.

the rising limb of the tracer pulse and released on the falling limb.

There are several wetland "compartments" that can serve to store inert solutes. The wetland sediments or media may reversibly sorb the tracer, and this possibility may be qualitatively checked with laboratory tests. However, there may be several other types of "parking places" in the wetland environment. These include stagnant pools of water, pore water associated with litter or clumps of filamentous algae, and the upper layer of soil pore water. Side pools are accessible by wind-driven cross currents. Litter and biomass pore waters are accessible by diffusion. Topsoil pore waters are accessible by diffusion and transpiration flows. All of these mechanisms have two common features: the presence of a storage location, and exchange with the main streams of water. At a simple level, a common model can be used for all.

There are two components to the dynamic model needed to track a tracer with the possibility of storage. The onedimensional mass balance for tracer for the flowing water is

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = \Phi(C_{\rm s} - C) \tag{B.40}$$

and the mass balance for storage is

$$\Omega \frac{\partial C_{\rm s}}{\partial t} = -\Phi(C_{\rm s} - C) \tag{B.41}$$

where

- C = tracer water concentration, mg/L
- $C_{\rm s}$  = tracer storage concentration, mg/L
- t = time, d
- u =actual water velocity along flow path, m/d
- x = distance along flow path, m
- $\Phi$  = exchange flow with storage, (m<sup>3</sup>/d)/m<sup>3</sup>
- $\Omega$  = storage ratio, m<sup>3</sup>/m<sup>3</sup>

These equations are those used to track pulses of constituents in chromatography, in which delays are due to adsorption. If there is equilibrium between storage and moving water, then  $C_s = KC$ . We may then add Equations B.40 and B.41, and write

$$(1 + \Omega K)\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} = 0$$
(B.42)

The factor  $(1 + \Omega K)$  is represented as  $\rho$ , the retardation factor for the system. In ideal circumstances, there would be no storage, and  $\rho$  will be 1. However, that will rarely be the case in real wetland environments. The best we can hope for is that  $\rho$  is close to unity, and, luckily, this is often the case (see, for instance, Richardson *et al.*, 2004).

Equations B.40 and B.41, either in continuous form or discretized, form the basis for the stage models of wetland tracer response. In continuous form, they have been termed the zones of the diminished mixing (ZDM) model, which has been calibrated to many FWS and HSSF wetlands (Werner and Kadlec, 2000a; 2000c). In discrete form, it is termed the finite stage model (Mangelson, 1972; U.S. EPA, 2000a). These will be discussed in more detail in the next section; here, the purpose is to determine the possible effects of storage and exchange on the parameterization of a tracer test.

The cases of water-dead zone storage and solid sorption are somewhat different in that dead water would normally be included in the calculation of nominal detention time, whereas solid sorption storage would not.

For the case of solid sorption storage, the effect of storage is to delay and broaden the tracer response curve. This means that the tracer detention time is lengthened compared to the nominal, and the number of TIS is reduced.

For the case of water storage in dead zones, the effect of storage is to accelerate and broaden the tracer-response curve. That means that the tracer detention time is shortened compared to the nominal, and the number of TIS is reduced.



**FIGURE B.16** The effects of reversible sorption on a tracer response for 4 TIS. The "no sorption" line is the forecast result for no sorption. The "sorption" line represents the result for 50% augmentation of water column storage on the solids.

#### An Example

These ideas are illustrated by considering a FWS wetland receiving 50 m<sup>3</sup>/d of water. It is assumed that the system contains an estimated 1,000 m<sup>3</sup> of water, computed from stage and bathymetric data. The nominal detention time is easily seen to be 20 days. We further suppose that the system behaves similar to 4 TIS. Equations B.40 and B.41 may be used to assess the effects of added sorption storage on the form of the tracer response. For illustration, suppose that sorption storage provides 50% augmentation of the storage in the water column and the exchange rate of tracer is 50% of the water flow rate. It is found that the measured tracer detention time would be 21.7 days and the system displays behavior characteristic of 2.2 TIS. The nonsorbing and sorbing tracer response curves are shown in Figure B.16.

The illustration is continued for the dead water case. Suppose that dead water storage provides 50% of the storage in the water column and the exchange rate of tracer is 50% of the water flow rate. It is found that the measured tracer detention time would be 13.8 days, and the system displays behavior characteristic of 1.7 TIS. The non-dead-water and dead-water tracer response curves are shown in Figure B.17.

#### **OTHER FLOW MODELS**

Whereas the TIS model described previously is the most popular flow model, other flow models are also used in the wetland literature.

#### PLUG FLOW WITH DISPERSION

Another model uses a dispersion process superimposed on a plug flow model (PFD). Mixing is presumed to follow a convective diffusion equation. Although the PFD model has been advocated for wetlands (e.g., Pardue *et al.*, 2000; Wang, 2006), it is doubtful whether it is the most appropriate



**FIGURE B.17** The effects of dead water storage on a tracer response for 4 TIS. The "no dead water" line is the forecast result for no dead water. The "dead water" line represents the result for 50% of water column in dead zone storage.

model of comparable complexity. The dispersion coefficient describes eddy transport of water elements both upstream and downstream. In FWS wetlands, such mixing may not occur because flow is often predominantly laminar.

A one-dimensional spatial model is chosen because analytical expressions are available for computation of pollutant removal for one-dimensional cases (Fogler, 1992). A twodimensional version requires a two-dimensional velocity field, which are virtually nonexistent for treatment wetlands. The tracer mass balance equation includes both spatial and temporal variability:

$$D\frac{\partial^2 C}{\partial x^2} - \frac{\partial(uC)}{\partial x} = \frac{\partial C}{\partial t}$$
(B.43)

where

u =actual water velocity, m/d

 $D = dispersion coefficient, m^2/d$ 

x = distance from inlet toward outlet, m

The appropriate wetland boundary conditions for this mass balance are known as the closed-closed boundary conditions (Fogler, 1992). These imply that no tracer can diffuse back from the wetland into the inlet pipe or up the exit structure at the wetland outlet. These are different from the open-open boundary conditions that are appropriate for river studies. There are analytical, closed form solutions to the latter case, which have led to their repeated misapplication to wetlands (Bavor et al., 1988; Stairs, 1993). There are no closed-form solutions for tracer responses for the wetland case, but numerical solutions to the closed-closed tracer mass balance have been available for more than three decades (Levenspiel, 1972). It is possible to calculate the dispersion constant that fits a particular dataset, although there are issues of accuracy. This model is not advocated here, because the PFD model is only infrequently applicable to treatment wetlands.

The dimensionless parameter that characterizes Equation B.43 is the Peclet number (Pe), or, its inverse, the wetland dispersion number (9).

$$\mathfrak{D} = \frac{D}{uL} = \frac{1}{\mathrm{Pe}} \tag{B.44}$$

where

 $\mathfrak{D}$  = wetland dispersion number, dimensionless

 $D = dispersion coefficient, m^2/d$ 

L = distance from inlet to outlet, m

Pe = Peclet number, dimensionless

u = superficial water velocity, m/d

A primary interesting result from the model is the dimensionless variance, which can be written in explicit form for the PFD model:

$$\sigma_{\theta}^{2} = 2\mathfrak{D} - 2\mathfrak{D}^{2}(1 - e^{-1/\mathfrak{D}}) \tag{B.45}$$

The principal problems with the PFD model to wetlands have to do with meeting the assumptions implicit in the model. Levenspiel (1972) notes as follows:

In trying to account for large extents of backmixing with the dispersion model we meet with numerous difficulties. With increased axial dispersion it becomes increasingly unlikely that the assumptions of the dispersion model will be satisfied by the real system.

The condition of an "intermediate" amount of axial dispersion (or less) should be met in order to apply the PFD model, which is nominally taken to be D < 0.025 (Levenspiel, 1972) and corresponds to about 20 TIS. The DTDs for FWS wetland systems are characterized by a large amount of apparent dispersion, with  $0.07 \le D \le 0.35$  (Kadlec, 1994). Therefore, generally, neither FWS nor HSSF wetlands are within the acceptable mixing range, although HSSF systems may sometimes be marginally within the range (see Tables 6.1 and 6.2, Chapter 6). However, a bigger obstacle to accepting the PFD model consists of the concentration profiles that are predicted for reactive constituents, because they predict features not seen in treatment wetlands.

The first-order concentration reduction produced by the closed-system PFD model is available in explicit form and is well known (see, for instance, Fogler, 1992):

$$\frac{(C-C^*)}{(C_o-C^*)} = \frac{4b \ e^{(Pe/2)}}{(1+b)^2 \ e^{(bPe/2)} - (1-b)^2 \ e^{(-bPe/2)}} \quad (B.46)$$
(a)  $b = \sqrt{1+4\frac{Da}{Da}}$ 

(b)  $Da = k\tau / h$  (B.47) (c) Pe = uL / D

where

 $D = dispersion coefficient, m^2/d$ 

L = distance from inlet to outlet, m

u = average superficial water velocity, m/d

This result is typically credited to Wehner and Wilhelm (1956).

Note that there are also two parameters in this reaction model: the rate coefficient k (or, equivalently, the Damköhler number Da), and the dispersion coefficient D. This formulation has been advocated for wetlands and ponds (Reed *et al.*, 1995; Crites and Tchobanoglous, 1998; Shilton and Mara, 2005; Crites *et al.*, 2006). However, the longitudinal profiles that this model predicts for large degrees of mixing are not realistic.

#### **PFD Longitudinal Profiles**

Longitudinal profiles may be used to test the validity of alternative modeling assumptions. For instance, the PFD model



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**FIGURE B.18** Fractional amount of reactant remaining for the first-order PFD model for closed-closed boundary conditions. The dispersion is D/uL = 0.20, and the reaction rate is  $Da = k\tau h = 3.0$ .

forecasts the concentration profile through the wetland by

$$\frac{C(x)}{C_i} = \frac{2e^{(x\text{Pe}/2)} \left[ (1+b)e^{(b\text{Pe}(1-x)/2)} - (1-b)e^{(-b\text{Pe}(1-x)/2)} \right]}{(1+b)^2 e^{(b\text{Pe}/2)} - (1-b)^2 e^{(-b\text{Pe}/2)}}$$
(B.48)

where

x = distance in flow direction, wetland, m C(x) = concentration at length x, g/m<sup>3</sup>

The longitudinal concentration profile is predicted to display an instantaneous drop at the wetland inlet. For  $\mathfrak{D} = 0.2$  and Da = 3, the decrease at the inlet is 30% (Figure B.18). For larger  $\mathfrak{D}$  (more dispersion), the instantaneous drop is even larger, increasing to 55% at  $\mathfrak{D} = 1.0$ . This unrealistically large concentration drop at the very start of the gradient has not been observed in wetland practice and, hence, the PFD model is not an acceptable alternative for most treatment wetland situations.

Interestingly, this predicted profile has only infrequently been examined in any of the literature pertaining to applications to ponds or wetlands, although the PFD model has been extensively utilized. In a pond environment, the situation is often one of considerable mixing because of wind and recirculation currents, and the concept of a sudden concentration change on entry is not unlikely. But in a treatment wetland, this model conceives of swirls that move back into the inlet region. That is a most unlikely scenario in a vegetated wetland environment.

# PARALLEL PATHS

The parallel paths model has been described previously as an example of a method for dealing with the long tails evidenced in some tracers. This model may also be easily coded in a spreadsheet, but there are five parameters: the flow split, plus the detention time, and the number of tanks along both paths. Some authors recommend the two-path response model (Keller and Bays, 2001; Chazarenc *et al.*, 2003; Wang, 2006; Wang *et al.*, 2006). However, if a two-path model is warranted, then there is something seriously wrong with the wetland. It is the wetland that needs improvement, not the model.

#### FINITE AND INFINITE STAGES

The breakthrough delay and the long tail may be described by a model that incorporates a plug flow component and sidetank storage in a series of units (Figure B.19). A single stage of



**FIGURE B.19** A single stage of the finite or infinite stage model. A plug flow unit is followed by a well-mixed unit that exchanges material with a side-storage unit.



**FIGURE B.20** Finite (N = 3) stage model of the tracer response of ENRP cell 4. The tracer detention time was 3.4 days. The plug flow fraction was 20%, active volume 40% and dead volume 40%. The exchange flow ratio was 0.4.

this model consists of a plug flow unit (of volume  $V_{\rm PF}$ ), followed by a well-mixed unit (of volume  $V_{\rm a}$ ) that exchanges material with a side-storage unit (of volume  $V_{\rm d}$ ). There are five parameters in this model: the number of stages, the detention time, the fraction plug flow, the fraction active well-mixed, and the exchange flow ratio. The exchange flow between  $V_{\rm a}$ and  $V_{\rm d}$  is *f*, and the ratio to the through-flow is *f/Q*. The finite stage model comprises a small number (2–5) of these stages in series. The infinite stage model utilizes a large number (~100) of the stages.

The concept of the finite stage model was advanced by a number of early authors (Hovorka, 1961; Mangelson, 1972; Levenspiel, 1972). Buffham *et al.* (1970) set forth a family of models that rest on the concept of water elements being delayed a number of times during passage through a packed bed. These are based on the abstraction that water would flow uniformly through the bed (plug flow) if it were not that elements are detained at points during their travel, and elements so detained eventually rejoin the main flow after a time delay.

The finite stage model can provide an excellent fit of data from both ponds and wetlands (Mangelson, 1972; Nolte and Associates, 1998b). An example of the fit is given for cell 4 of the ENRP (Figure B.20). In this case, the response model is supported by the visual tracer study (see Figure B.8), in which the main flow path and side storages may easily be seen.

Werner and Kadlec (2000c) showed that the model could assume a limiting form for a very large number of stages. They termed this the zones of diminished mixing (ZDM) model, which contains four parameters: the detention time, the fraction dead zones, the fraction bypassing, and a dispersion number for the main flow path. Martinez and Wise (2003a) used the infinite stage model via the code of Runkel (1998), which is called OTIS (one-dimensional transport with inflow and storage).

Stage models, by virtue of their one-dimensional character, are not capable of providing a good fit in situations where there is clearly more than one flow path (Martinez and Wise, 2003a).

Stage models do not lend themselves to an easy representation for computing pollutant removal. Thus, although they often can do an excellent job of representing the tracer response, they are of limited use in wetland evaluation and design.

#### COMPUTATIONAL FLUID DYNAMICS (CFD)

Many treatment wetlands are not linear in their design and assume irregular shapes with irregular bathymetry. Flow distribution may be at a point along the inlet boundary rather than distributed across the width of the wetland. Additionally, vegetation density may not be spatially uniform. Under such circumstances, the internal flow patterns are variable in at least two dimensions, lateral and longitudinal. As with all other models, vertical averaging has always been utilized, although that assumption is questionable under many wetland circumstances. Flow modeling involves solution of mass and momentum balances on a two-dimensional grid, together with a tracer mass balance. This procedure has been utilized, for example, by Walker (1998), Persson et al. (1999), Koskiaho (2003), Wörman and Kronnäs (2005), Jenkins and Greenway (2005), Kjellin et al. (2006), and Lightbody et al. (2007). Several software packages are available for this purpose, including RMA4, MIKE-21, HYDRA3, and HYDRUS2D.

The advantage of CFD modeling is the ability to explore the consequences of alterations in the basin morphology on the volumetric and DTD efficiencies of a system. For instance, the use of point inlets and outlets has the conceptual potential to create dead zones in the corners of a rectangular wetland. This may be tested with CFD, and indeed, the corners are predicted to be excluded from the flow (Figure B.21). The CFD simulations of Koskiaho (2003) indicate that the flow can miss both the inlet and exit corners in rectangular wetlands. For this case, there are field data to confirm the predicted effect (Stairs, 1993; Stairs and Moore, 1994). The FWS wetland had an aspect ratio of L:W = 3:1 and was



**FIGURE B.21** The penetration of new water into a FWS wetland according to a 2-D simulation model. Note that there may be recirculation and that corners do not "see" the new water. (From Walker (1998) *Ecological Engineering* 10(3): 247–262. Reprinted with permission.)

operated with and without a distribution header across the inlet. Tracer testing indicated a volumetric efficiency of 84% with the header, and 66% without. With the header, NTIS = 4.5, and without, NTIS = 3.3. The field data indicate an overall hydraulic efficiency  $\lambda = 46\%$  for no header and  $\lambda = 65\%$  with a header. The simulation results of Persson *et al.* (1999) and Jenkins and Greenway (2005) provide reasonable forecasts of overall hydraulic efficiency  $\lambda$  of about 40–45% for unvegetated ponds of similar aspect ratio.

# PREDICTIONS FROM TIS AND CFD FLOW MODELING

The goal for treatment wetland design is to be able to predict the efficiencies of wetlands based on their morphology. Simulation results have been used to provide a few first indications of such relationships.

#### UNVEGETATED SYSTEMS

Flat-bottom systems without plants have often been investigated. The effect of length-to-width ratios for ponds on dispersion has been reported by several researchers, and a summary of results is presented by Shilton and Mara (2005). Although the various pond regressions are for deep water environments compared to FWS wetlands, there is a trend, in all investigations, for the dispersion number (D/uL) to decrease as L:W increases. In other words, longer and narrower ponds display characteristics closer to plug flow, although still displaying behaviors characterized by a small number of TIS. Jenkins and Greenway (2005) present simulation results for unvegetated FWS wetlands with point inlets and outlets, which may be expressed as

$$e_{\rm V} = 1 - e^{(-0.3L/W)} \tag{B.49}$$

Thackson *et al.* (1987) presented a similar correlation for data from shallow ponds that substantially agrees with these simulation results (Walker, 1998; Jenkins and Greenway, 2005). Likewise, the *N*TIS value is high for high values of L:W. Therefore, for unvegetated FWS wetlands, there is essentially no advantage in L:W ratios being greater than ten. However, it must be noted that these results are for point inlets and outlets, which are not efficient and probably should not be used.

#### VEGETATED SYSTEMS

The presence of vegetation will markedly change the hydraulics of the wetland by creating less dispersion and higher efficiencies (Kadlec, 1994). For example, the simulation results of Persson *et al.* (1999) showed that the full vegetation of the South Gippsland, Australia, wetland would have increased  $e_V$  from 0.39 to 0.69 and *N*TIS from 5.7 to 15, compared to its existing condition. That existing condition was a channel from inlet to outlet, with only fringing vegetation.

The three principal variables associated with vegetation are: (1) percent cover, (2) stem density, and (3) orientation of patches. When vegetation is oriented in the flow direction, typically along the wetland edges, it is termed *fringing vegetation* (Persson *et al.*, 1999; Jenkins and Greenway, 2005). When the orientation of patches is across the flow direction, it is termed *banded vegetation*. The simulation results of Jenkins and Greenway indicate that the use of banded vegetation is more efficient than fringing vegetation because of the shortcircuiting issue caused by the flow resistance in the fringes. Results from field studies in Florida (periphyton field cell tracer tests, unpublished data) and California (New River wetlands test results, unpublished data) tend to validate these simulation studies (Figure B.22).

If the vegetation density of a fringe is increased, then more flow is forced down the central channel, and efficiency drops. This was the simulation result of Jenkins and Greenway (2005), and the field result of Dal Cin and Persson (2000) and Stern *et al.* (2001).

#### BATHYMETRY

Deep channels in the direction of flow cause shortcircuiting, whereas deep zones across the flow direction have little effect on flow patterns. The channelization effect is intuitively bad, and has been borne out in both simulation and field studies. It does little or no good to create the channel with meanders, that is, a serpentine deep channel from inlet to outlet (Persson *et al.*, 1999).

The use of transverse deep zones in treatment wetlands has been advocated as promoting internal water redistribution and thus the improvement of volumetric and DTD efficiencies (Knight and Iverson, 1990; Knight, 1992; Knight *et al.*, 1994; Knight *et al.*, 2004). However, simulation results suggest that  $e_V$  is little changed by deep zones (0.80 versus 0.81), and  $e_{DTD}$ only modestly improved (0.96 versus 0.92) for the Gippsland,



**FIGURE B.22** (A color version of this figure follows page 550) Rhodamine dye dispersing through an inlet deep zone, with a spikerush band providing resistance to shortcircuiting. (From CH2M Hill (2003a) *PSTA Research and Demonstration Project, Phases 1, 2, and 3 Summary Report*. prepared for the South Florida Water Management District (March 2003).)

Australia, wetland (Persson *et al.*, 1999). At the Tres Rios, Arizona, site, 12 FWS wetlands were operated as triplicates of 0, 1, 2, and 3 internal deep zones, and tracer tested (Whitmer, 1998). Analysis of that data via least-squares parameter estimation provided values for  $\tau$  and *N*. The resulting efficiencies are shown in Table B.4 for the 12 research wetlands. There was essentially no difference in volumetric efficiency or *N*TIS due to the number of deep zones, and hence none in hydraulic efficiency ( $\alpha = 0.05$ ) (Kadlec, 2007).

Knight *et al.* (1994) operated a set of six treatment wetlands receiving treated paper-pulp-mill effluent for two years. Two internal deep zones comprising 25, 35, and 45% of the area were included in three of the six (Table B.5). Although there was variability in flow (different HLRs) and aspect ratios (2.5, 5, and 10), the authors concluded that there was improvement in nitrogen removal performance due to deep zones. Tracer data from that project are here reanalyzed, and characterized by a tanks-in-series (TIS) detention time distribution. The effect of deep zones was to decrease the number

**TABLE B.4** 

of TIS. However, for the two larger cell pairs, the volumetric efficiency was improved by deep-zone addition (Table B.5).

#### Hummocks and Islands

Any wetland feature that protrudes from the water causes a reduction in wetland water volume and surface area compared to the wetland in its absence. Therefore, there is a penalty for such features in terms of the detention time or hydraulic loading. The argument has been made that islands (hummocks are small islands) promote better flow distribution and thus increase the DTD efficiency of the system (e.g., Thullen *et al.*, 2005); however, field tests at Tres Rios do not support that contention (city of Phoenix, unpublished data).

According to CFD simulations for shallow ponds, this effect is present in wetlands without vegetation (Persson *et al.*, 1999). However, CFD results for the Ekeby, Sweden, FWS wetland led to the conclusion that "According to the simulations, the constructed deep zones and islands had only

| Internal Deep<br>Zones | Percent<br>Deep | NTIS            | Volumetric<br>Efficiency<br>(e <sub>v</sub> ) | DTD<br>Efficiency<br>(e <sub>DTD</sub> ) | Hydraulic Efficiency<br>(λ) |
|------------------------|-----------------|-----------------|---|--|-----------------------------|
| 0                      | 12.5            | $3.30 \pm 0.79$ | $0.56 \pm 0.19$                               | $0.69 \pm 0.07$                          | $0.38 \pm 0.11$             |
| 1                      | 20              | $3.93 \pm 0.31$ | $0.64\pm0.20$                                 | $0.74\pm0.02$                            | $0.47 \pm 0.14$             |
| 2                      | 28              | $4.00\pm0.40$   | $0.67\pm0.08$                                 | $0.75 \pm 0.03$                          | $0.50 \pm 0.04$             |
| 3                      | 35              | $3.63 \pm 0.06$ | $0.65\pm0.08$                                 | $0.72\pm0.01$                            | $0.47 \pm 0.06$             |
|                        | Mean            | 3.70            | 0.63  | 0.73                                     | 0.46                        |

Hydraulic Efficiency Measures for the Tres Rios Research Cells

Note: Means ± standard deviations.

TARIER 5

| Performance of the Champion Wetlands, July 1991–June 1993 |       |       |       |       |       |       |
|---|-------|-------|-------|-------|-------|-------|
| Wetland   | Α     | В     | С     | D     | E     | F     |
| Area (m <sup>2</sup> )                                    | 4,048 | 4,048 | 2,024 | 2,024 | 1,012 | 1,012 |
| Aspect  | 2.47  | 2.47  | 4.94  | 4.94  | 9.88  | 9.88  |
| DZ %  | 5     | 25    | 5     | 35    | 5     | 45    |
| Depth (m)   | 0.270 | 0.380 | 0.250 | 0.480 | 0.270 | 0.580 |
| HLR (cm/d)  | 3.16  | 3.38  | 4.83  | 3.99  | 7.82  | 8.13  |
| Nominal HRT (d)   | 8.54  | 11.23 | 5.17  | 12.04 | 3.45  | 7.13  |
| NTIS  | 4.60  | 3.60  | 4.00  | 3.50  | 10.70 | 2.00  |
| Volume efficiency   | 0.63  | 0.81  | 0.43  | 0.82  | 0.91  | 0.74  |
| Hydraulic efficiency                                      | 0.49  | 0.59  | 0.32  | 0.59  | 0.83  | 0.37  |

| Performance of the Cham | pion Wetlands, Jul | y 1991–June 1993 |
|-------------------------|--------------------|------------------|

Source: Hydraulic and concentration data are from Knight et al. (1994) TAPPI Journal 77(5): 240-245. The DTD and k-value analyses are from this work.

a minor effect on the residence time distribution" (Kjellin et al., 2006). The effect of islands in unvegetated systems is to divert flow toward corner zones that would otherwise not be accessed by the flowing water. However, in vegetated systems, the flow is predominantly directed by the vegetation, and not the bathymetry.

Underwater features, such as cross-flow benches or "speed bumps," have been utilized for the expressed purpose of redistributing flow. According to CFD simulations, this is effective for unvegatated systems (Persson et al., 1999). The field experience of Simi and Mitchell (1999) was that speed bumps and deep zones promoted mixing, such that a FWS wetland of L:W = 2 behaved approximately as NTIS = 2.

#### **Peninsulas and Sinuous Flow**

Because of the strong effect of the length-to-width ratio that prevails for unvegetated FWS wetlands, it has been surmised that it is very advantageous to utilize high L:W for vegetated systems. Very often, the site boundaries do not allow linear wetlands of great length and, consequently, the strategy of folding the wetland several times is used to lengthen the L: W ratio. Such "back-and-forth" flow paths require the use of internal divider berms separating the passes of the flow path. This configuration is sometimes referred to as a sinuous path system in wetlands, but the equivalent in ponds is the use of baffles. Baffles improve the efficiencies of ponds, according to both CFD and field data. Vega et al. (2003) used simulation to predict that a pond of 2:1 aspect would show an improvement of  $e_v$  from 74 to 84%, and NTIS from 3.94 to 5.5, for the addition of two baffles (18:1 with baffles). Lloyd et al. (2003) measured an increase in  $e_v$  from 42 to 50%, and NTIS from 1.46 to 1.57, for two baffles in a pond of L:W =4:1 (35:1 with baffles). Thus, improvement is found for the use of sinuous paths for unvegetated systems. However, pond systems often have low NTIS and low volumetric efficiency compared to vegetated wetlands.

The L:W ratio increases as the square of the number of passes. Sinuous and nonsinuous vegetated wetlands were run side by side at Listowel, Ontario, but unfortunately, no tracer tests were run (Herskowitz, 1986). However, there were improvements in pollutant removal performance for the sinuous systems. A tracer test was run on a FWS wetland of overall aspect L:W = 1:1, with three divider berms creating a four-pass back-and-forth flow pattern at Hillsdale, Michigan. The nominal flow aspect ratio was thus 16:1. Recovery was 70%, and NTIS = 4.3, but the volumetric efficiency was only 20-30%. Evidently flow followed small channels within each pass and failed to reach the majority of side areas.

In contrast, a side-by-side tracer test of a one-pass and a three-pass system of the same overall aspect (5:1) showed major differences (CH2M Hill, 2003a). Recoveries were similar but low (45 and 46%). The nonsinuous system (L:W = 5:1) had NTIS = 9 and  $e_{\rm V}$  = 0.88, whereas the sinuous system (L:W = 45) had NTIS = 25 and  $e_v = 0.58$ . As a consequence, the hydraulic efficiency of the sinuous system was lower ( $\lambda = 0.56$ ) than that of the nonsinuous system  $(\lambda = 0.78).$ 

These studies are insufficient to draw conclusions about the efficacy of sinuous designs, but do provide preliminary indications that the length-to-width advantage may be overridden by the creation of numerous corner dead zones. Additionally, the divider berms occupy a portion of the footprint and so contribute to a loss of wetland area.

#### COMPARTMENTALIZATION

Efficiencies may be increased by subdividing the wetland into a number of cells in series. This has the effect of lowering wind fetch and thus preventing large-scale recirculation. Compartmentalization also causes the water to be collected at each cell outlet, thus blending the high- and low-speed flow elements and then redistributing them.

On a theoretical basis, the effect on detention time is simply to break up the total detention time into pieces proportional to the volumes contained in the component cells:

$$\tau = \sum_{j=1}^{n} \tau_j \tag{B.50}$$

where

n = number of compartments

j = detention time in the *jth* compartment, d

However, the effect on the DTD efficiency is a bit more complicated. For cells in series, the variance of the tracer response for the system is the sum of variances for the individual cells (Levenspiel, 1972):

$$\sigma^2 = \sum_{j=1}^n \sigma_j^2 \tag{B.51}$$

where

 $\sigma_i^2$  = variance change in the *jth* compartment, d<sup>2</sup>

This may be related to the detention time and number of TIS for each compartment. From Equations B.22 and B.24,

$$\sigma_j^2 = \frac{\tau_j^2}{N_j} \tag{B.52}$$

where then the system is represented by:

 $N_i = \text{TIS}$  for the *jth* compartment

$$\frac{\tau^2}{N} = \sum_{j=1}^n \frac{\tau_j^2}{N_j} \tag{B.53}$$

or

$$\frac{1}{N} = \sum_{j=1}^{n} \left[ \frac{\tau_j^2}{\tau^2} \right] \frac{1}{N_j}$$
(B.54)

In other words, the reciprocal *N*TIS values are additive in proportion to the square of the detention time fractions. If the compartments are all of equal size, then the *N*TIS values are simply additive, but not otherwise. For example, if 90% of the wetland is a compartment that behaves as 4 TIS, and the remaining 10% is a compartment that behaves as 10 TIS, then the system will act like 4.9 TIS.

It may easily be shown that pollutant removal is improved by compartmentalization because it moves the system closer to plug flow. However, for a fixed footprint, the wetland area is decreased because of the interior divider berms, and therefore multiple compartmentalization is not necessarily advantageous.

At the present time, it is necessary to rely on simulation results because there are not side-by-side tracer tests of compartmentalized and noncompartmentalized systems.

#### TRACER TESTING PROTOCOLS

#### TRACER SELECTION

Many different tracers have been used for hydraulic analysis of treatment wetlands. Desirable properties are that it is soluble in water, does not react with the pollutants or wetland constituents, occurs at low background levels within the wetland, may be easily analyzed, has low toxicity, and does not influence the flow pattern in a significant way (Headley and Kadlec, 2007). The three most common choices for wetland tracers have been fluorescent dyes and lithium or bromide salts. In FWS wetlands, both dyes and salts have been successfully used. Studies in HSSF and VF wetlands are generally performed using salt tracers.

Radioactive tracers, such as tritium, have very good tracer properties and have been used in constructed wetlands (Crohn *et al.*, 2005; Xu *et al.*, 2005; Kjellin *et al.*, 2006). However, the use of radioactive substances in wetlands is often precluded by regulatory requirements and specific analytical requirements.

#### **Dye Tracers**

Dyes have advantages of low detection limits, zero natural background, and low relative cost. However, they are susceptible to both photodegradation and biodegradation (Dierberg and DeBusk, 2005). This can complicate the analysis of tracer data, as discussed above.

Rhodamine WT is the most commonly used dye, mainly because of availability. Dissolved solids have no effect below about 600 mg/L, and pH has no effect above pH = 6, although the level of fluorescence is temperature sensitive, changing about 2% per degree Celsius (Smart and Laidlaw, 1977). Rhodamine WT is susceptible to biodegradation, photolysis, and adsorption onto organic solids, detritus, and some plastics (Smart and Laidlaw, 1977; Lin *et al.*, 2003a; Dierberg and DeBusk, 2005). Due to the above characteristics, rhodamine WT should only be used in short-term tests ( $\tau_n$  less than about three days) and within environments that are not highly organic.

Rhodamine WT is typically measured using fluorescence spectrophotometry at wavelength 558 nm and an emission wavelength of 580 nm (Smart and Laidlaw, 1977; Simi and Mitchell, 1999). Other dyes that have been used with varying degrees of success include eriochrome acid red (Bowmer, 1987), and uranine and eosine (Netter and Bischofsberger, 1990; Netter, 1994).

At high concentrations, fluorescent dyes are visible in FWS wetlands. For instance, just a cupful of RWT can easily be tracked through a 1-ha system. It is also feasible to use RWT for visible studies on large wetlands, such as the 147-ha cell 4 of the ENRP (see Figure B.8) (Dierberg *et al.*, 2005). Visible studies are useful for establishing blatant shortcircuits, and cross-levee leakage.

#### Salt Tracers

Bromide and lithium are the most extensively used ionic tracers, mainly due to their perceived noninteractive character and ease of analysis. They are added as solutions of sodium or potassium bromide, or lithium chloride, and have yielded reliable results in numerous wetland studies (Bowmer, 1987; Netter, 1994; King *et al.*, 1997; Rash and Liehr, 1999; Drizo *et al.*, 2000; Grismer *et al.*, 2001; Keller and Bays, 2001; Tanner *et al.*, 2002a; Lin *et al.*, 2003; García *et al.*, 2004b; Smith *et al.*, 2005). Lithium and bromide are not susceptible to degradation but are capable of being taken up by wetland plants and other organisms to a limited extent (Kung, 1990; Whitmer *et al.*, 2000; Xu *et al.*, 2004; Parsons *et al.*, 2004). Perhaps more serious is the loss of any tracer, inert or not, caused by the movement of water from the water column to the rhizosphere due to the transpiration flux. Tracer is drawn into the root zone, where it is effectively lost during the relatively brief duration of a tracer experiment.

Background concentrations of lithium are typically very low; for instance  $30 \pm 14 \mu g/L$  (mean  $\pm$  s.d.; range 4–50 for 20 FWS systems). Bromide may be present in natural waters at concentrations well above detection; for instance 420  $\pm$ 760  $\mu g/L$  (mean  $\pm$  s.d.; range 5–3,500 for 20 FWS systems). Bromide is typically analyzed via ion chromatography, although specific ion electrodes are available. Lithium can be measured using atomic absorption spectrometry (AAS) or inductively coupled plasma–optical emission spectrometry (ICP-OES).

Chazarenc *et al.* (2003) used high concentrations (67,000 mg/L) of sodium chloride solution as a tracer in a HSSF and measured conductivity in order to derive DTDs. They reported tracer recovery rates exceeding 78% from eight individual tracer studies. Sodium chloride can represent a relatively inexpensive option that can be easily monitored and logged in the field using electrical conductivity probes. However, high salt concentrations may have a negative effect on wetland biota and possibly treatment. Wörman and Kronnäs (2005) used potassium iodide as the tracer at the Alhagen, Sweden, wetland.

#### Amount of Tracer

The mass of tracer in the impulse addition is based on the expected dilution, the method detection limit of the analytical techniques, and the background concentration of the tracer in the wetland system after dilution. During the introduction of the tracer impulse into the influent stream, the concentration should be considerably higher than both the analytical method detection limit and background concentration of tracer in the wetland. A target for the peak effluent concentration in the response might therefore be at least 20–50 times the background concentration, and at least 50 times the detection limit.

It is perhaps easier to plan in terms of the average concentration desired in the response curve. The peak-to-mean ratio (ratio of the peak tracer concentration to the mean tracer concentration over a period of three detention times) is typically 2–3 for FWS wetlands, and 4–5 for HSSF wetlands. The benchmark concentration can be defined as the mass of tracer added divided by the nominal volume of water in the wetland:

$$C_{\text{bench}} = \frac{M}{V_{\text{n}}} \tag{B.55}$$

where

 $C_{\text{bench}}$  = benchmark concentration, g/m<sup>3</sup> = mg/L M = mass of tracer added, g  $V_{\text{n}}$  = nominal wetland water volume, m<sup>3</sup>

The reader is reminded that the nominal wetland water volume for subsurface flow wetlands must take into account the porosity of the granular medium in the wetland bed. This benchmark concentration will be approximately 30–70% of the peak concentration. Keller and Bays (2001) suggest that the quantity of tracer added, if assumed to mix uniformly throughout the volume of the wetland, should achieve a benchmark concentration at least 10 to 20 times the background concentration.

#### **Density Stratification Problems with Salt Tracers**

Tracer materials are most often available as either solids (e.g., NaBr, LiCl) or as concentrated solutions. These as-received materials are usually dissolved or diluted to form the tracer solution to be added, which is here designated to have concentration  $C_{\rm dose}$ . Care should be exercised in preparing a solution to be dosed into the wetland because there can be large heat-of-solution effects upon dissolution. Most tests are conducted as impulse tests, which implies that the tracer should be dumped into the wetland inlet structure all at once. However, at high  $C_{\rm dose}$  concentrations, the density of the dosing solution may be substantially higher than that of the ambient water in the wetland to which it is added, causing the tracer pulse to sink to the bottom of the wetland.

In FWS wetlands, this situation is exacerbated by the presence of an inlet deep zone that serves as a repository for the dense slug of tracer. This effect is worsened by the transpiration flux in a FWS wetland, which draws water selectively from the wetland bottom and consequently may "pull" the dense tracer from the bottom of the water column into the soil matrix. Under such circumstances, tracer recovery will be poor. Although the typical interpretation of FWS wetland water flow is vertically averaged, water moves more slowly across the wetland bottom due to drag forces. This can cause the flow of the tracer through the wetland to be retarded as it slowly creeps along the bottom and stagnates in depressions. Consequently, density stratification can lead to a significant distortion in the DTD (Schmid *et al.*, 2004a; 2004b).

To avoid the density stratification issue, the tracer concentration should not be so high as to result in a significant difference in density between the ambient wetland water and the tracer impulse when it is introduced into the wetland. For typical tracers salts, at 25°C, density equations are as follows (Söhnel and Novotny, 1985); all  $\mathbb{R}^2 \ge 0.9995$ :

Lithium chloride 
$$\rho = 1.0000 + (5.0327 \times 10^{-7})C_{dose}$$
  
(B.56)
Potassium bromide  $\rho = 1.0132 + (6.9267 \times 10^{-7})C_{dose}$ (B.58)

Sodium chloride  $\rho = 0.9986 + (2.6123 \times 10^{-7})C_{dose}$ (B.59)

where

 $C_{\text{dose}}$  = concentration of tracer dose solution, g/m<sup>3</sup> = mg/L  $\rho$  = density of tracer dose solution, g/cm<sup>3</sup>

It is known that, in lakes, a density difference of about 1% is enough to maintain stratification. In their teaching lab experiment to demonstrate this effect, Wetzel and Likens (1991) use a density difference of 1.5%. It is therefore not surprising that Chazarenc *et al.* (2003) observed tracer stratification in full-scale HSSF systems at a density difference of 3.4%.

There is also a body of anecdotal evidence that implicates density effects in anomalous tracer tests. For example, several LiCl tests were run by the South Florida Water Management District on test cell wetlands with instantaneous dosing with 78,000 mg/L lithium chloride. The density difference would have been on the order of 3.9%. Recoveries were quite variable, with some as low as 23%. Rousseau et al. (2006) reported "losing" a dose of high-concentration lithium in an SSF wetland pilot but finding it residing on the wetland bottom. The studies of Whitmer et al. (2000) displayed very low recoveries of sodium bromide, impulsedosed into deep zones at about 200,000 mg/L. The estimated density difference would have been approximately 14.6%. Although the loss was attributed to plant uptake, it seems highly probable that the dense bromide accumulated in the inlet deep zones and stayed there. Schmid et al. (2004a; 2004b) performed detailed experiments using salt tracers in shallow-water flumes, intended to emulate FWS wetlands. The presence of plastic dowels in the water column (which were used to represent plants) assisted in the prevention of stratification. Nonetheless, stratification in these idealized laboratory channels was found to exist for concentrations on the order of 150 mg/L of sodium chloride. Drizo et al. (2000) dosed HSSF mesocosms with potassium bromide at 20,000 mg/L, which has a density 1.2% greater than water. The tracer was found on the bottom of all mesocosms, whether planted or unplanted.

Density stratification may be ameliorated by aeration of the wetland. An aerated HSSF wetland in Anamosa, Iowa, was dosed with 142,000 mg/L potassium bromide (11.2% more dense than water) (Nivala *et al.*, 2004). The measured recovery of 85% and volumetric efficiency of 91% were indicative of lack of stratification (Nivala, 2005). Nonetheless, at 25% of the bed length, the concentration peak in the top layer (15 cm) was five times higher than that in the deep layer (45 cm).

Based on these findings, it is suggested that the density of the tracer impulse should be a great deal less than 1% of the density of the ambient wetland water in order to minimize the risk of density effects. Clearly, it is also useful to promote as much turbulence as possible at the point of water introduction so that the tracer is further diluted by the primary inlet water flow.

Fortunately, the density difference problem can also be alleviated by prolonging the period of tracer dose introduction. This effectively dilutes the dose concentration with incoming water prior to the wetland. In effect, the impulse is replaced by a "square wave" tracer input. The clock for the test is set to zero at the midpoint of the inlet tracer delivery time series. There will then be no error in the computation of the tracer detention time. The variance of the tracer outlet response is adjusted by subtracting the variance of the inlet pulse (Levenspiel, 1972). In this way, the dose concentration may be diluted by a very large factor.

## SAMPLING FREQUENCY AND DURATION

A quantitative tracer test requires definition of the full response curve, from the pretest background through the rising and falling limbs of the distribution and back down to a posttest plateau. This requires sampling for a long-enough period and at a suitable frequency to adequately describe the tracer response curve. Thus, an estimate of the likely DTD of the wetland should be made based on nominal parameters to design a sampling regime. Important aspects of the DTD to be considered when determining sampling frequency are the steeply rising limb of the peak concentration profile and the long, declining tail. However, tracer responses often cannot be accurately forecast. It is therefore prudent to collect and store more samples than anticipated to be needed because lithium and bromide do not degrade during storage. These supplementary samples can then be analyzed retroactively if they are deemed to be necessary based on analysis of the primary sample set.

About 30-40 sample points are normally adequate to define the response curve spread over about three nominal detention times. A minimal sampling frequency of 24 points is illustrated in Figure B.23. These are more densely spaced in the early portion of the response to capture the rise in concentration. A lesser frequency is needed far out on the tail. Where the flow rate is somewhat variable (stormwater wetlands, for instance), flow-weighted sampling will generally be the best way to ensure that accurate sampling of the tracer response curve is achieved. In any case, it is necessary to record both the time of sampling and volume of water that has passed through the sample point, as these are required in interpreting the variable-flow tracer-response data. The use of automatic samplers is of great benefit. They can be configured to collect samples at regular time intervals, or alternatively to collect samples on a flow-weighted basis.



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FIGURE B.23 The concentration of the peak of a 4-TIS response is 2.74 times the mean concentration over three detention times.

Sampling should begin immediately prior to tracer injection to identify the background concentration at the time of the tracer study. The greatest sampling frequency is required at times when the concentration is changing most rapidly (that is, around the time of the peak in concentration). The rise typically begins at 10–30% of  $\tau_n$ . The peak will typically occur at 50–90% of  $\tau_n$ .

Following the expected peak in tracer concentration, the sampling frequency can be progressively decreased. To adequately capture the declining tail of the DTD sampling is typically required for an extended period. Examination of tracer responses from the numerous available experiments indicates that the impulse response is typically complete after four  $\tau_n$ . In general, care should be taken not to allow too much volume to exit without being sampled. Otherwise, a spike or dip in the concentration could be partially or even completely missed, particularly at high flow rates (Werner and Kadlec, 2000c).

#### Hydrologic Measurements

To quantify the results of a tracer test, the complete hydrologic conditions must be known. The flow rates entering and exiting the wetland should be continuously logged over the duration of the tracer study. Rainfall can be important, and should be measured at the site. Evapotranspiration and seepage may be estimated. These combine to give the wetland water budget. In the context of a tracer test, the flows are necessary to compute the tracer mass balance and the recovery of tracer in the outflow. Effects of rain and *ET* are usually small, but not always (Chazarenc *et al.*, 2004).

It is important to know the wetland water volume because it is required to compute the nominal detention time  $(\tau_n)$ . In turn,  $\tau_n$  is used to calculate the volumetric efficiency of the wetland  $e_v = \tau/\tau_n$ . For FWS wetlands, the bathymetry is used to obtain the water volume. As noted in Chapter 2, these measurements are somewhat ambiguous because, typically, the wetland bottom is not well defined. For FWS wetlands, the water volume requires knowledge of the upper water surface and the porosity of the media. That porosity may be accurately known for the bare media, but the extent of pore blockage by roots, biofilms, and accreted solids is typically not accurately known.

#### **Internal Sampling**

In addition to inflow/outflow points, the tracer response at interior wetland points can be of some use in assessing the spatial characteristics of the wetland. There are two distinct cases to be considered: the individual cells in a multicompartment wetland, and points interior to an individual cell. The difference is considerable because, in the former case, the water volumetric flow rate past the measurement is known, whereas in the latter case it is not. Thus, it is possible to get a flow-weighted concentration at a cell outlet, whereas it is not possible at an interior point.

For cell networks with single inlets and outlets, there is no ambiguity, and efficient cells may be distinguished from inefficient cells. If there are multiple inlets and outlets, then averaging assumptions must be made, but analysis is still unambiguous. Perhaps the most involved cellwise tracer testing was performed at the Orlando Easterly treatment wetland, where the first 15 of 17 cells were tracer tested (Martinez and Wise, 2001) (see Figure B.24). These cells varied widely in their hydraulic behavior (see Table B.1). Results of the testing confirmed the need to re-establish the bathymetry of several cells (Sees, 2005).

Another multicell wetland tracer study was conducted at Lakeland, Florida (CH2M Hill, 1999; Keller and Bays, 2001). Four cells in series, of 81, 77, 166, and 30 ha, were tested separately, with recoveries of 67–106% and volumetric efficiencies of 0.04–0.45. Cell 2 had  $\tau = 0.7$  d, and a  $\tau_n = 19.1$  d, indicating very serious shortcircuiting. In such cell studies, it is feasible to measure the individual structure flows, and test protocols are the same as for single-cell wetlands. However, if a single pulse is to be followed through multiple cells in series, analysis must recognize that detention times (first moments) and variances (second moments) are additive (Levenspiel, 1972).

Both FWS and HSSF wetlands may also be sampled for tracer response at internal points, along and across the flow



FIGURE B.24 The layout of the Orlando Easterly treatment wetlands. The first 15 cells were tracer tested. (From Martinez and Wise (2003b) *Journal of Environmental Engineering (ASCE)* 129(6): 553–560. Reprinted with permission.)

direction, and at varying depths. In contrast to cell studies, the flow fraction passing such internal points is unknown.

Internal tracer studies on FWS have been reported by Kadlec (2001a), Jawitz and White (2002), Crohn et al. (2005), Dierberg et al. (2005), and Harvey et al. (2005). These studies confirm some intuitively obvious phenomena. The Des Plaines River wetlands studies showed that the shallow and backwater areas of irregular FWS systems saw relatively less tracer than the main flow path (Kadlec, 2001a). Jawitz and White (2002) found that vegetated barrier strips perpendicular to flow produced only small variations in tracer arrival times across the flow direction, regardless of high (aspect ratio = 45) or low (aspect ratio = 5) length-to-width ratio. Crohn *et al.* (2005) also saw only small variation in arrival times in a sequence of cross-deep zones at the Hemet, Califorinia, wetland. However, remnant ditches and roads in cell 4 of the ENRP caused shortcircuiting that was visible via rhodamine (see Figure B.8) but also quantified by quantitative analysis of the dye (Dierberg et al., 2005). Harvey et al. (2005) measured water velocities and conducted tracer studies to obtain the volume average water velocity. They found that the average velocity was only about two thirds of the spatial average due to the preferential velocity measurements being in open water zones.

Internal tracer sampling for HSSF systems was done in the researches of Spangler *et al.* (1976b), Fisher (1990), Pilgrim *et al.* (1992), Marsteiner *et al.* (1996; 1997), Drizo *et al.* (2000), García *et al.* (2003a; 2003b; 2004b), Melton (2005), and Nivala (2005). These studies provide a general picture of tracer preferentially moving through the bottom layers of gravel, regardless of whether it arrived there due to density or distribution (Figure B.25). When the bed floods, tracer testing indicates that almost all the flow is overland across the top of the gravel (Spangler *et al.*, 1976b). Flow in HSSF beds is typically nonuniform from side to side, as seen in Figure B.2. Time-series sampling at multiple points across the flow path often shows this imbalance in the form of quite dissimilar tracer responses (for instance, see Chapter 6, Figure 6.17). Studies by Pilgrim *et al.* (1992), Marsteiner (1997), Melton (2005), and Nivala (2005) show differing degrees of internal tracer response imbalance. However, internal patterns of tracer response are of no quantitative value in analyzing wetland behavior because of the lack of flow information to accompany them.

The old literature on tracer analysis describes internal average sampling (cross-transects) as "through the wall" sampling (Levenspiel, 1972). In the wetland context, this corresponds to arithmetic averaging of samples taken at a number of points perpendicular to the flow direction (Kadlec, 2000). Averages of tracer concentrations taken across the flow direction are not the same as the flow-weighted concentration at that point in the overall travel path; in fact, they are often very much different (Levenspiel and Turner, 1970). As described in Chapter 2, different sampling points across the flow path led to very different internal tracer response curves at the Benton, Kentucky, HSSF wetland. The same result was found at a Texas on-site facility (Melton, 2005). Thus, spatially averaged internal cross-sampling is likely to be valid only if done in a deep zone that ensures complete mixing of the various flow elements (Crohn et al., 2005).

### **ANALYZING TRACER DATA**

The goal of tracer studies is to understand the volumetric and DTD efficiencies of a particular wetland. Although the methods of processing data are straightforward, there are some nuances of data utilization that require explanation.



FIGURE B.25 Tracer responses for locations in and beneath the rhizosphere in a HSSF wetland. (From Fisher (1990) In *Constructed Wetlands in Water Pollution Control*. Cooper and Findlater (Eds.), Pergamon Press, Oxford, United Kingdom. Reprinted with permission.)

#### **Baselines and Tails**

In all cases, there will be a background concentration of the tracer in the wetland water. The value is not necessarily constant, but may vary during the test either due to random processes or to a (slight) time trend. Thus, the background concentration after the test may not be the same as before the test, either due to random effects or extremely slow bleedback of some small fraction of the test material. In other words, the tail of the response may not come back down to the starting background concentration. An example is shown in Figure B.4 for Cell 2 of the ENRP in Florida. Over 2 tons of lithium chloride were added to this 167-ha FWS wetland, with care taken to prevent density effects. The initial lithium in the wetland outflow was about 8-9 µg/L. After the test, some 35 to 45 days later, the outflow lithium appeared to no longer have a trend, and was  $12-13 \mu g/L$ . It is not known if the higher background is due to added tracer remaining after very long times, or due to other causes.

It is intuitive that the initial background should be subtracted from the measured concentrations to keep track of the added lithium. For the ENRP tracer study, the corrected recovery of tracer for this test was 98%. However, the fact that the response did not return to the original baseline has a fairly large effect on the computed tracer detention time. The small concentrations of tracer that occur at long times are disproportionately important in the numerical evaluation of this summation, as seen in Table B.2. In the ENRP example, the tracer detention time is 13 days, calculated over the entire 47 d of the test, and about 12% of that is due to the material leaving in the plateau at 35–47 days. This "tail error" has long been known to possibly seriously affect tracer test results (Curl and McMillan, 1966).

There are two procedures that have been used to deemphasize the long-term plateau effect. First, the tail of the response ought to be exponential, according to the generally accepted modeling results (Vereecken *et al.*, 1999). Therefore, the tail of the response maybe fitted with an exponential function, relying upon the higher concentrations prior to the tail to set the rate of decline. This procedure has been followed by some wetland researchers (Dal Cin and Persson, 2000; Wang, 2006). Often, the "tail" of the measured exit concentration distribution is poorly defined. Sometimes the sampling is terminated too soon; sometimes the final baseline does not return to the starting zero. Under these circumstances, the tail may be determined as an exponentially decreasing function, extrapolated from the data points past the second inflection of the response.

The alternative procedure is to perform a least-squares fit of the selected DTD to the data, which places equal emphasis on the errors across the entire test. The result of this procedure for the ENRP Cell 2 example is shown in Figure B.4.

### TRACER MASS RECOVERY

Closure of the tracer mass balance is a prerequisite to a good tracer test. Large losses or apparent gains of tracer, compared to the amount dosed, are a signal that something is awry with the water flows, or that the chosen tracer is undergoing extensive nonconservative behavior (Kadlec, 1994). The measure of the tracer test reliability is the recovery percentage. Outflow rates and tracer concentrations are combined and summed to compute the total mass in the exit tracer pulse:

$$M_{\rm o} = \int_{0}^{\infty} Q_{\rm o} C(t) dt = ? = M_{\rm i}$$
 (B.60)

where

 $C(t) = \text{exit tracer concentration, g/m}^3 = \text{mg/L}$ 

 $M_i$  = mass of tracer introduced with inflow, g

- $M_0$  = mass of tracer exiting with outflow, g
- $Q_0$  = average outflow rate, m<sup>3</sup>/d

This permits a tracer mass balance and computation of the percentage tracer recovery. The concentrations used in this summation are first corrected for background. Secondly, if there are anomalies with the measured concentrations in the tail zone, or if the tail has been missed due to premature cessation of the test, then an exponential "patch" may be applied. Alternatively, a least-squares fit may be conducted. Typically, treatment wetland tracer recoveries in the range of 80–120% are considered acceptable.

# POLLUTANT REMOVAL EFFECTS

A primary reason for tracer analysis is to be able to account for hydraulic effects and thus reduce that part of the variability in pollutant reductions. First and foremost, it is desirable to know the real retention time, or equivalently the volumetric efficiency. Secondly, the distribution of detention times is important via the DTD efficiency.

The models discussed in this appendix are all concerned with correctly describing the behavior of an inert material as it passes through the wetland. However, the important target is correctly describing reactive materials. To understand the implications for DTD model selection, a hypothetical case is considered. Suppose that the wetland behaves like four well-mixed units in series, and suppose that the contaminant in question follows first-order kinetics and has a zero background concentration. For this illustration, the amount (concentration) of pollutant remaining at the outflow will be considered as the measure of performance.

The first questions are: Does it matter if there are four TIS? Isn't plug flow good enough? To answer those, a variety of rate coefficients and detention times may be considered for the two cases. It is the product  $Da = k\tau/h$  that controls both cases. Figure B.26 shows that, for small Da, which corresponds to small removal of the contaminant, there is not much difference between models. If Da < 1, for which there is more than 40% of the material remaining, there is only a maximum of 10% difference. Either model could be effectively used if performance was to be in this low range.

However, if removals in excess of 90% are contemplated, then there are very big differences between the plug flow and 4 TIS forecasts. The ratio of fractions remaining grows from a factor of two at 90% 4 TIS conversion to a factor of twenty at 98% 4 TIS conversion. Therefore, if high removals are contemplated, it is very important to correctly characterize wetland internal hydraulics.

# THE TAIL OF THE DTD

The next issue is: How careful do we have to be in describing the details of the tracer response? Does it matter if the tail end of the DTD is accurately modeled? To answer these questions, we consider the origins of the unreacted material in the wetland outflow. If there are shortcircuits, they will carry the contaminant to the wetland outlet before they have had much time to react. If there are dead zones, water will remain there a long time and be fully reacted. These ideas may be quantified by considering the detention times for the unreacted materials. We therefore continue the illustration and calculate the fraction of the unreacted effluent material corresponding to different detention times. This is the same calculation as for degrading tracer that was considered earlier. Figure B.27 shows the travel time distribution of the unreacted material leaving for Da = 2. The material leaving primarily followed short detention paths: 98% of the leftovers came from detentions less than 1.5 times the average detention time, and 85% from detentions less than 1.0 times the average detention time. The tail is irrelevant to the determination of the amount of unreacted material.

The example chosen is representative of only one wetland hydraulics and one operating condition. However, exploration of the TIS model shows that the conclusion of tail irrelevancy is strengthened for lower numbers of TIS (TIS < 4), and



FIGURE B.26 Variation of plug flow and 4 TIS model results for various rate constants.



**FIGURE B.27** Origins of the unreacted material leaving a hypothetical 4-TIS wetland for Da = 2. The removal is 86.5% under these conditions, and the remaining reactant cumulative distribution refers to the remaining 13.5%. The DTD is scaled by a factor of ten.

also for non-TIS DTDs with longer and bigger tails. Higher Damköhler numbers, equivalent to higher removal percentages, shift the origin of unreacted material to even shorter detention times. For Da = 1, or 60% unreacted material, 99% of the leftovers come from detentions less than 2.0 times the average detention time, and 75% from detentions less than 1.0 times the average detention time.

## THE HEAD OF THE DTD

The front end of the tracer response represents what is generically called *shortcircuiting*. In pathological situations, a large peak occurs far in advance of the nominal detention time. However, even in "normal" situations, it is often necessary to correctly account for the water and associated pollutants that leave the wetland early.

Given the insensitivity of pollutant removal to the tail of the DTD, it is logical to ask whether the head of the DTD is critical to pollutant removal. There is usually a delay of some magnitude before any tracer arrives at the wetland outlet, which is larger for HSSF wetlands than for FWS wetlands (see Figures B.5 and B.6). For 35 FWS wetland tracer tests, the first tracer breakthrough occurred at  $23 \pm 11\%$  of the tracer detention time. For 32 HSSF wetland tracer tests, the first tracer breakthrough occurred at  $37 \pm 14\%$  of the tracer detention time.

For some guidance, we return to the 4-TIS illustration. It is found that, for low rates of reaction, the early-departing material carries only a small fraction of the unreacted total. For FWS behavior, and for Da = 1, or 60% unreacted material, only 2% of the leftovers come from detentions less than 0.25 times the average detention time. For HSSF behavior, and for Da = 5, or 4% unreacted material, 48% of the leftovers come from detentions less than 0.4 times the average detention time. It is clear that care must be taken to provide a

proper representation of the leading portion of the DTD if it is necessary to characterize high removals.

The two simplest choices for describing the breakthrough lag are the TIS model, and the TIS model modified to have a leading plug flow component (see Equation B.27).

In general, this three-parameter (N,  $\tau$ ,  $t_D$ ) fit of the DTD will give a better fit to data than the two-parameter TIS fit, especially if there is a substantial delay. However, it adds some complexity to pollutant removal modeling, and so it must be examined for necessity. As an illustration, the basis for comparison is taken to be a wetland that behaves like 4 TIS after a time delay. The "head effect" is known to be most important for high removal percentages, so the Damköhler number is selected to be Da = 3, corresponding to 95% removal in plug flow, or 5.0% remaining. For 4 TIS, the percent remaining is 10.65%. The TIS model appears to give a reasonable least-squares fit to the delayed tracer response (Figure B.28), but it does turn up a bit sooner than the delay. Because of the delay, the number of TIS grows with the delay, from N = 4 for no delay to N = 17.9 for a delay of 50% of the detention time.

The amounts of pollutant remaining also differ for the delayed "data" and the least-squares *N*TIS fit. The *N*TIS fit produces greater amounts remaining: 7% more for a delay of 23% of the detention time (FWS), and 10% more for a delay of 37% of the detention time (HSSF). Therefore, if the wetland is contemplated to remove less than 95% of a contaminant, it is probably acceptable to use the two-parameter *N*TIS fit rather than the three-parameter delayed *N*TIS fit of the tracer response.

It is also possible to use the moment method for fitting the *N*TIS model. Earlier it was seen that this method emphasized the tail of the DTD, but it also emphasizes the head of the DTD. Of course, that is exactly what is needed to better account for the delay.



**FIGURE B.28** Tracer response with a delay. The points were generated from a delay of  $\theta = 0.5$  together with a 4-TIS response. The tracer detention time is  $\theta = 1.5$ . A least-squares fit of the TIS model gives N = 9.7 for this case.

### STRATEGIES FOR DATA FITTING

The preceding model exploration exercises lead to suggestions regarding the strategy of fitting and using tracer data. These are

- The "tail" of the tracer DTD is not generally an important contributor to the amount of a pollutant that will pass through the wetland unreacted. It is probably not necessary to add parameters to tracer models to better account for long "tails."
- The "head" of the tracer DTD is important for situations where high contaminant removals are contemplated. The important feature is the existence of a delay before any tracer is observed in the wetland outflow. The presence of such a delay contributes to a better pattern of flow by virtue of adding a plug flow component to the response. Typically, for high removals, the contaminant residual is reduced 25% in FWS wetlands, and 35% in HSSF wetlands, compared to systems with no delay.

The delay may be accounted by adding a third parameter to the *N*TIS model. Alternatively, it is probably acceptable to use the *N*TIS model.

In the data processing in this book, we have used the simpler two-parameter approach.

## **R**EACTIONS ALONG FLOW PATHS FOR FWS WETLANDS

In addition to distributions of detention times (across flow fractions), other factors exist that can influence overall Damköhler numbers. One class of possibilities arises from spatial distributions of wetland water depths and vegetation density. Distributions of Damköhler numbers across flow fractions may be created due to both k and t being related to vegetation density and depth.

Kadlec (2000) postulated that patterns of vegetation can strongly influence the perceived reaction rates in treatment wetlands, as well as affect the velocity and amount of water that passes through a given region of a FWS wetland. This presumption was explored in more detail by Carleton (2002).

As an example, consider a wetland with parallel flow paths of unequal vegetation density. High-velocity flow paths result from lack of vegetative resistance; low-velocity paths from large vegetative resistance (Hosokawa and Horie, 1992; Jenkins and Greenway, 2005). In addition, wetland data show that water velocity is strongly depth dependent (Kadlec and Knight, 1996). For laminar flow under a fixed water surface gradient,

$$u = \frac{a'h^b S^c}{X} = \frac{ah^b}{X}$$
(B.61)

$$t = \frac{L}{u} = \frac{LX}{ah^b}$$
(B.62)

where

*a*, *b*, *c* = constants,  $d^{-1}$  *h* = water depth, m *L* = length of wetland cell, m *X* = submerged vegetation surface area density,  $m^2/m^3$  *S* = slope of the water surface, m/m *t* = time, d *u* = superficial water velocity, m/d

Different values of the exponent *b* apply to different vegetation types. Here, for purposes of illustration, b = 1 is chosen. These relations state that, for a specified overall water slope, the water velocity is inversely proportional to the immersed vegetation surface area and directly proportional to the depth. Therefore, the detention time along any flow path is directly proportional to the depth. Consequently, cross-flow spatial distributions of *h* and *X* create a distribution of detention times, as detailed by Carleton (2002).

Depth and vegetation density effects on water velocity have been investigated, and an improved understanding is emerging (e.g., Hall and Freeman, 1994). Those same variables exert influence on pollutant-reduction rates, but the quantification of those effects is still in early stages. There have been some definitive studies that establish the influence of water depth on volumetric rate coefficients; for instance, the data of Gearheart *et al.* (1989) that clearly demonstrated k for BOD was inversely proportional to depth. In other cases, the relationship is less clear. Stem density has been found to be an important determinant of rate coefficients in some cases (Lakhsman, 1982) but not in others.

The wetland vegetation density influences many wetland pollutant removal processes. This may be due to the biofilms that coat submerged litter, roots, and stems, or to the biogeochemical cycling that creates net uptake to new sediments (Khatiwada and Polprasert, 1999a). Many removal processes are associated with surface area, such as mass transfer or microbial reactions. The active reaction zone may therefore be on the bottom, in the water column, or a combination. If the active zone is exclusively associated with immersed surfaces, the rate coefficient is presumptively proportional to X, as observed by Smith *et al.* (2000) for nitrate reduction. Conversely, many wetlands display constancy of areal rate, and thus the volumetric rate coefficients used in previous sections are inversely proportional to depth:

$$k = \frac{\beta X}{h} \tag{B.63}$$

There may be other influences on the rate coefficient, such as enhancement of mass transfer via increasing velocity. Here, such velocity dependence is assumed to be absent, as a limiting case.

The effect of parallel spatial patterns of vegetation density and water depth is to create spatial patterns of the removal rate constant. The effects of both types of distribution on pollutant removal are thus two-fold. Flows through low vegetation density regions are fast and ineffective, whereas flows through high vegetation density regions are slow and effective. Flows through high-depth regions are fast and ineffective, while flows through low-depth regions are slow and effective. Combination of Equations B.62 and B.63 for b = 1 gives

$$kt = \left(\frac{a\beta}{L}\right)t^2 = \gamma t^2 \tag{B.64}$$

where

$$\gamma = (a\beta/L) = \text{constant}, d^2$$

This is the same result presented by Carleton (2002). The fraction remaining (for  $C^* = 0$ ) along a parallel flow path of vegetation resistance X and detention time t is

$$\frac{C}{C_{\rm i}} = e^{(-\gamma t^2)} \tag{B.65}$$

Under this potential scenario, the fraction of pollutant remaining along a given flow path decreases exponentially with the square of the detention time along that path. It is the result of a direct interrelation of k, X, h, and, t and the corresponding wetland circumstance is termed the "*Xhkt*" condition. Note that there is a serious consequence of the *Xhkt* condition, in that travel time in a flow system is no longer equivalent to batch time in a non-flow-through system. Any batch experiment is necessarily done under conditions of constant X and variable time, which is not possible in a flow system if travel time is dependent on X. This nonequivalence has been experimentally explored by Stein *et al.* (2003).

Vegetation density and depth distributions can produce a false impression of plug flow conditions. Poor treatment along fast flow paths produces a faster-than-average rate of pollutant removal at longer detention times, which precludes plateaus in concentration profiles. Kadlec (2000) points out that the interdependence of k and detention time leads to an imputed PFR rate constant (from a PFR fit of the Xhkt data) that depends upon the hydraulic loading rate. Here, it is additionally noted that the *Xhkt* condition may yield the appearance of PFR performance for an NTIS wetland. To illustrate, the behavior of a 3-TIS wetland is examined under the Xhkt assumption for a zero-background concentration. The coefficient  $\gamma = 0.25 \, d^{-2}$  yields flow-weighted outflow concentrations that decrease with increasing mean detention time (Figure B.29). This hypothetical data may be fitted with a relaxed TIS model, where the variable P represents the



**FIGURE B.29** Fraction remaining for a single compound undergoing first-order degradation or removal in a wetland with variable vegetation density on parallel flow paths. The points are computed from Equation B.38, coupled to a 3-TIS DTD. The line represents the *N*TIS model, as well as the PFR model.

combined effect of the number of tanks, *N*, and weathering of the contaminant, as discussed in Chapter 6. The results for this model are P = 1,834,  $k_{app} = 0.358 \text{ d}^{-1}$ , and  $R^2 = 0.982$ . This high *P*-value corresponds to an apparent plug flow condition.

Thus, both increases and decreases in the apparent TIS number can result from internally distributed parameters. Interestingly, no combination of distribution effects has been found here that caused performance behavior to stray far from an envelope bracketed by apparent plug flow and apparent TIS.

# SUMMARY

Tracer testing offers a means of better understanding of the processes controlling the performance of treatment wetlands. Results are now available from hundreds of tracer tests of FWS and HSSF systems. Despite the appealing simplicity of the plug flow assumption that has repeatedly been made, and continues to be made, in the literature, it is abundantly clear that neither FWS nor HSSF systems behave as plug flow. Furthermore, many wetlands have significant fractions of the water column that are dead zones, which are not directly

flushed by flowing water, as evidenced by volumetric efficiencies less than unity. The interpretation of wetland pollutant removal data, and the design for pollutant removal, are facilitated by a knowledge of the volumetric efficiency, as well as the DTD efficiency of the wetland.

The proper technique of conducting a tracer test has not always been adhered to, thus causing difficulties in interpretation. Density stratification, degradable and sorbable tracers, and lack of hydrologic control have obscured results in some cases. Nonetheless, a great deal of progress has been made in the last ten years toward better understanding of the features of treatment wetlands and how they affect hydraulic behavior. It has been possible to apply quite sophisticated models to represent tracer responses, but that level of detail is not always necessary for interpretation of contaminant removals. Importantly, this new understanding moves the science of wetland performance toward greater confidence levels. Although the old plug flow approach may have been sufficient for interpolating key process data in for design purposes, extrapolation beyond the existing data set was quite often disastrous. Tracer results enable a new generation of models that are better able to describe systems over wider ranges of operation conditions.