FRESHWATER INFLOWS TO TEXAS BAYS AND ESTUARIES: A REGIONAL-SCALE REVIEW, SYNTHESIS, AND RECOMMENDATIONS

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Outline

- How I got started
- Regulatory environment
- What we have learned over 30+ years
- New Book
  - Synthesis Efforts
  - Management solutions
  - Engagement (StoryMap)

Wesley Seale Dam,
Lake Corpus Christi

A Simple Question by Gary Powell Started it all

Died 2MAR2013

- Summer of 1986, Gary (with Bob Jones) convened a group of new UTMSI scientists (Ed Buskey, Ken Dunton, Paul Montagna, Terry Whitledge), and existing staff (Tony Amos, Scott Holt, Rick Kalke, Peter Thomas)
- He asked a simple question:

  How much freshwater must flow into San Antonio Bay to maintain estuary health?

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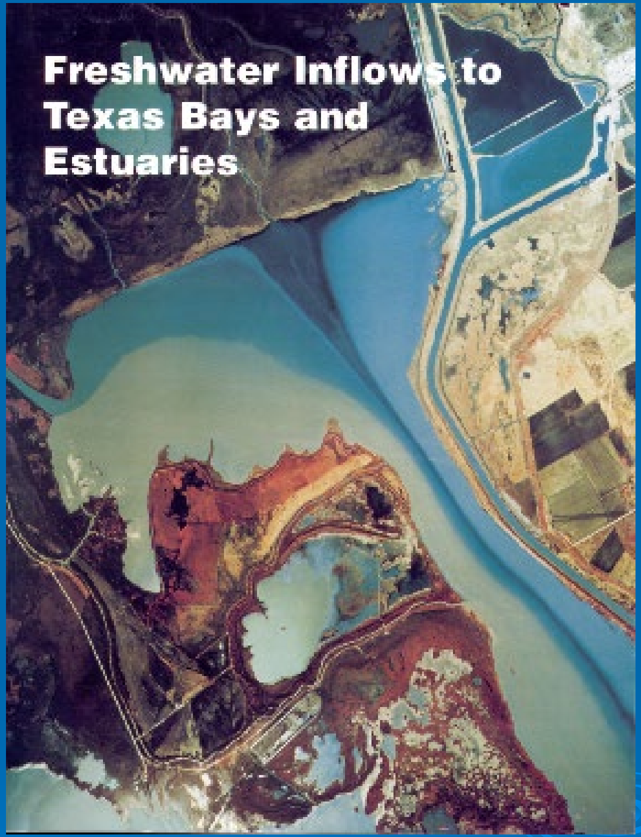
OCEAN REFLECTIONS

HOW A SIMPLE QUESTION ABOUT FRESHWATER INFLOW TO ESTUARIES SHAPED A CAREER

Paul A. Montagna

Culminated In a Synthesis

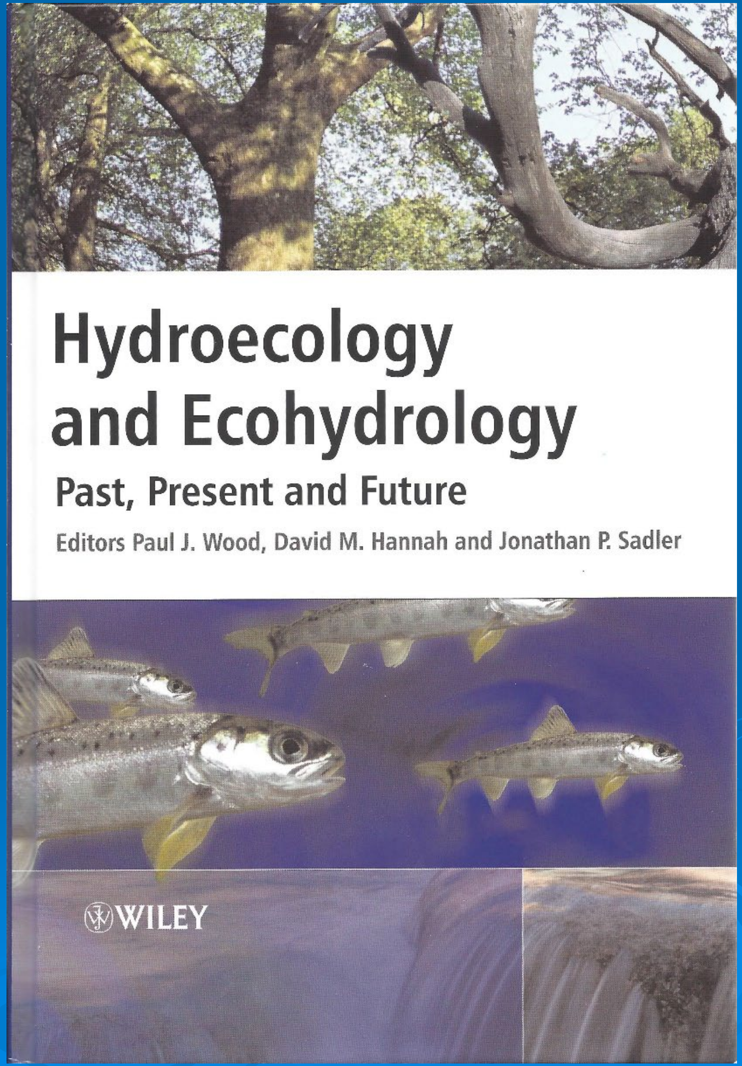
- *Freshwater Inflow to Texas Bays and Estuaries*
  - *Ecological Relationships and Methods for Determinations of Needs*
- William Longley (TWDB), Editor, 1994
- Jointly with TPWD
- Hydrology, Salinity, and TXBLEND everywhere in State
- Nutrient and sediment loading most places
- Detailed ecological process studies and TEXEMPT on San Antonio Bay only



A New Subdiscipline is Born

- What I didn't realize, was that a whole new subdiscipline of ecology was being created
- An integrative science that provides a foundation for sustainable management of water resources
- Textbook in 2007
- Journal *Ecohydrology* established in 2008

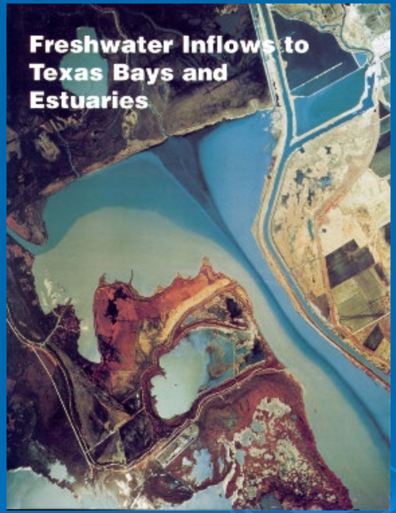
2008



2007

History of Inflow Legislation in Texas

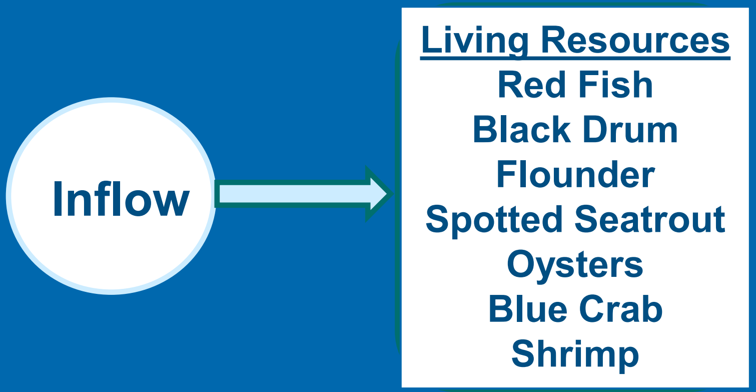
- 1985: House Bill 2
  - Established data collection programs necessary to "support a sound ecological environment"
    - Protected 7 species: White shrimp, brown shrimp, blue crab, oyster, red drum, spotted seatrout, black drum
  - 1994: *Freshwater Inflow to Texas Bays and Estuaries*



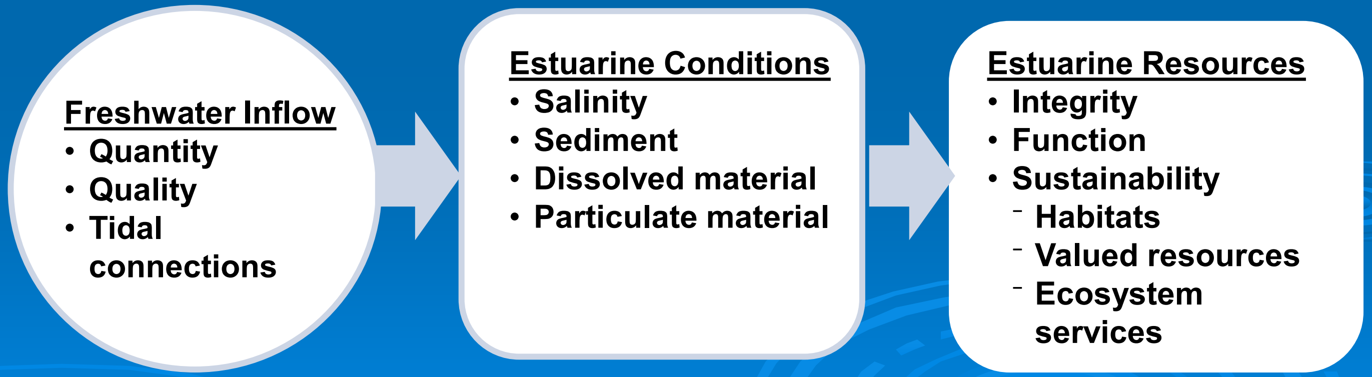
- 2007: Senate Bill 3
  - Required environmental flow regime standards for geographic segments state-wide
  - Standard must be "adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats . . ."
  - Standards adopted between 2011 - 2014

History of Inflow Science in Texas

- Reflects two major eras:
  - 1985 HB2
    - Influenced by riverine studies
    - Species-based approach



  - 2007 SB3
    - Evolving estuary science
    - Ecosystem-based approach

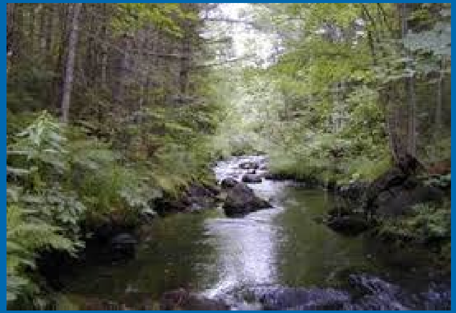


Difference in Instream vs. Inflow Approaches

- Freshwater systems: Flow defines habitat

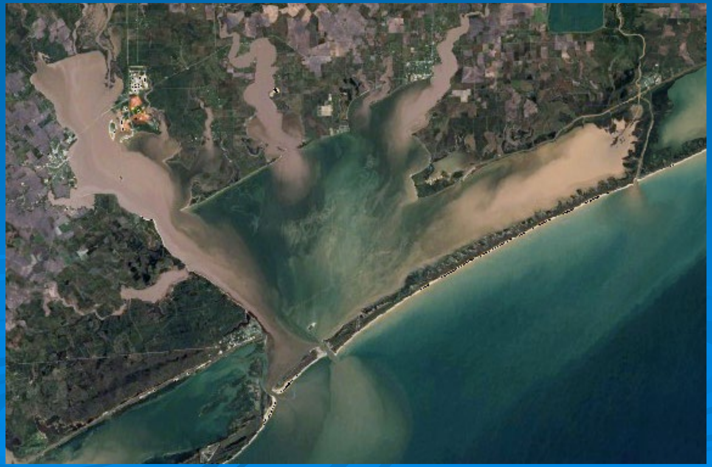

Rapid


Riffle


Run

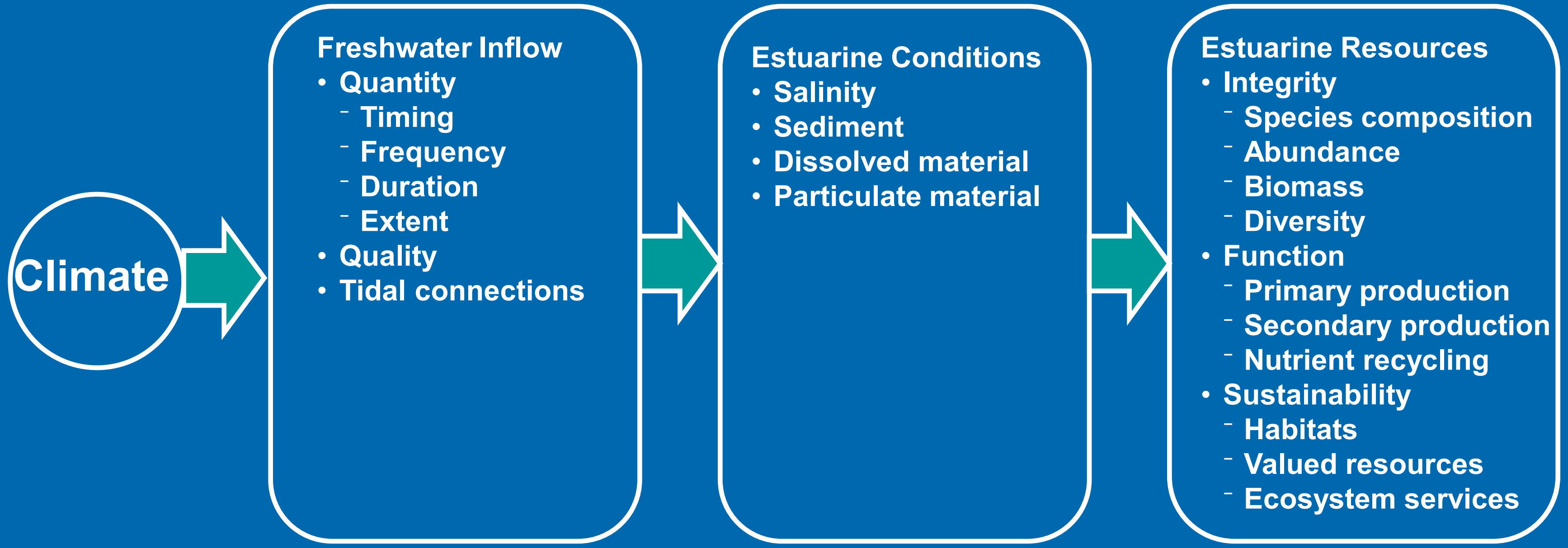

Pool

- Coastal waters: Flow defines conditions and conditions create estuary habitat



Turbidity plumes in Lavaca and Matagorda Bays after a flood

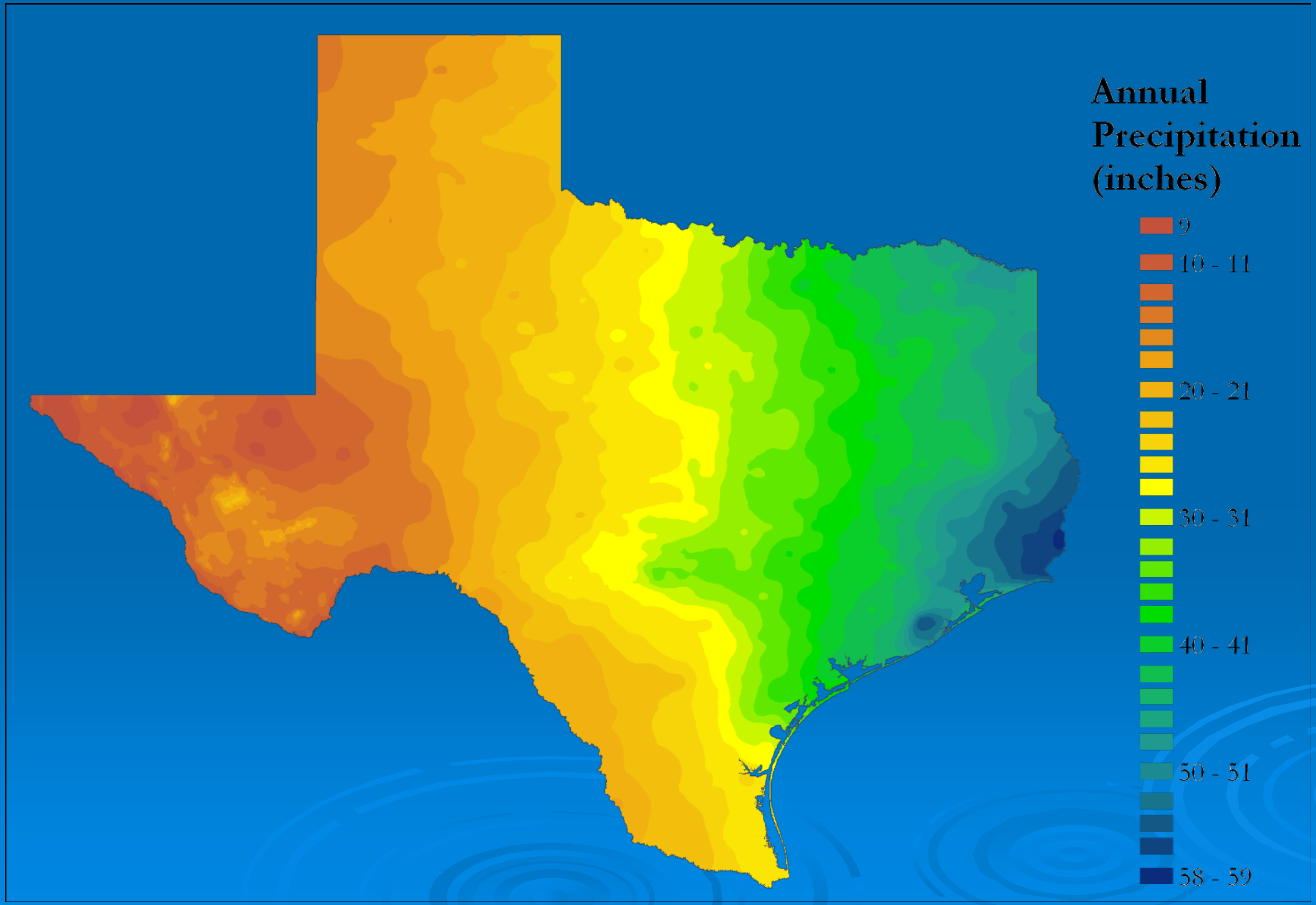
Inflow Has Indirect Effects on Biological Resources: “Domino Theory”



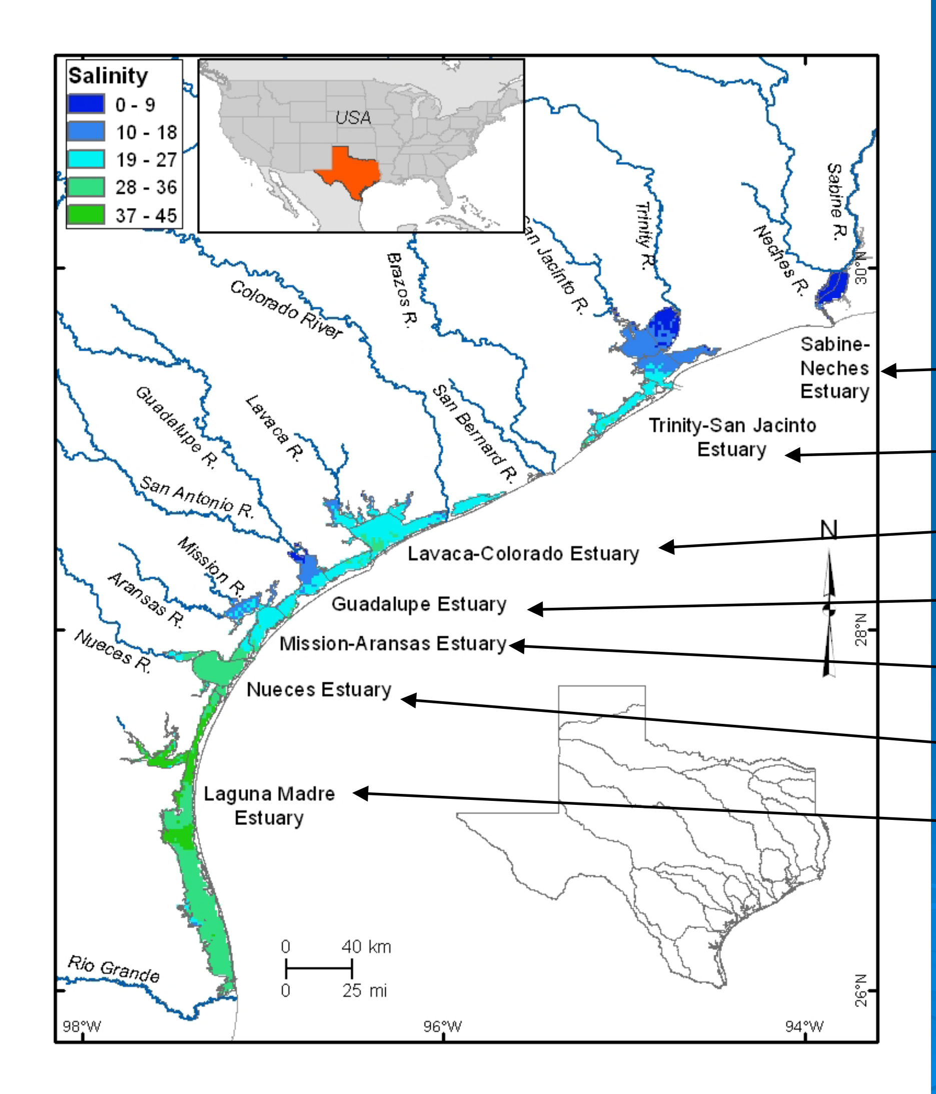
Evolution of the idea:

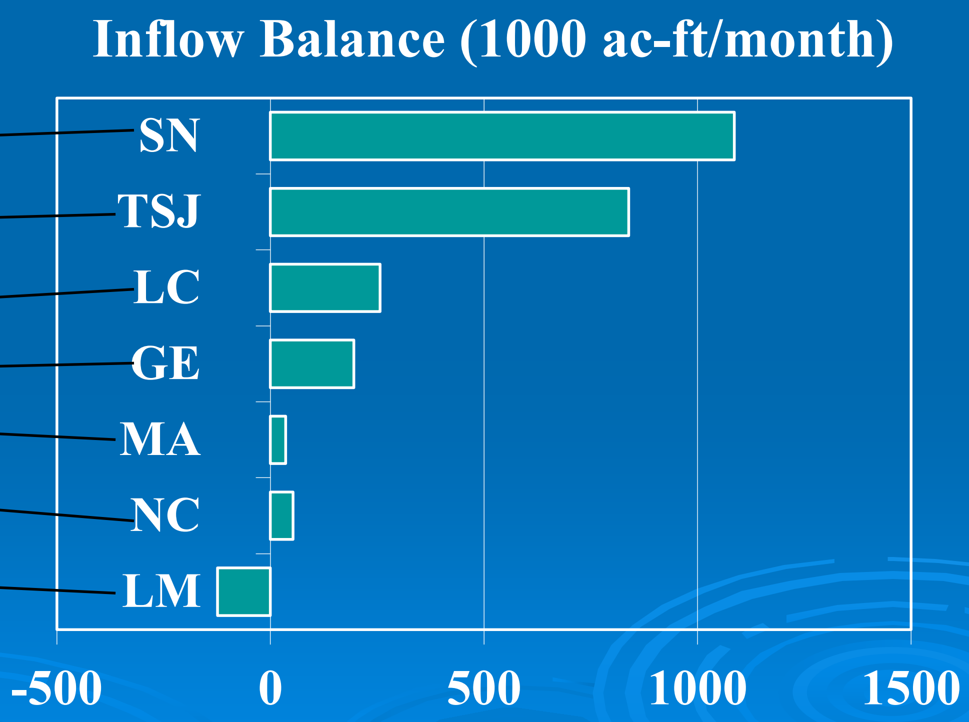
- Alber (2002) *Estuaries* 25:1246-1261 https://doi.org/10.1007/BF02692222
- Science Advisory Committee (2009) Methodologies for Establishing a Freshwater Inflow Regime https://hdl.handle.net/1969.6/94344
- Palmer et al. (2011) *Hydrobiologia* 667:49-67 https://doi.org/10.1007/s10750-011-0637-0
- Montagna et al. (2013) *Hydrological Change and Estuarine Dynamics* https://doi.org/10.1007/978-1-4614-5833-3
- Montagna (2021) *Gulf and Caribbean Research* 32:14 pp. https://doi.org/10.18785/gcr.3201.04

There is a Rainfall Gradient From East to West in Texas



Texas Coast-Wide Inflow Gradient Provides a Perfect Natural Experiment



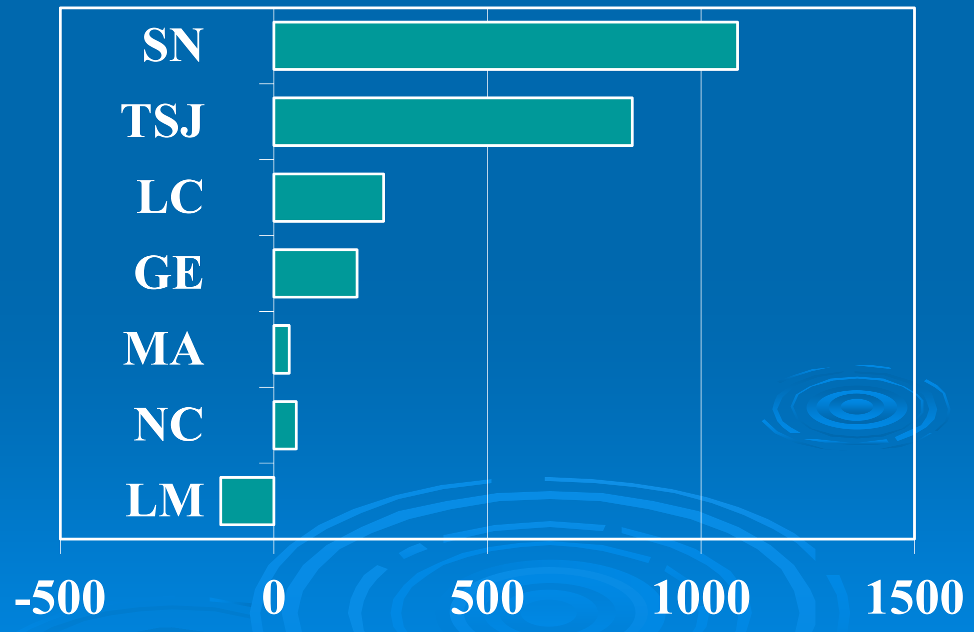


Inflow (TWDB): 1941-2009
Salinity (TPWD): 1977-2015

Texas Estuary Comparisons

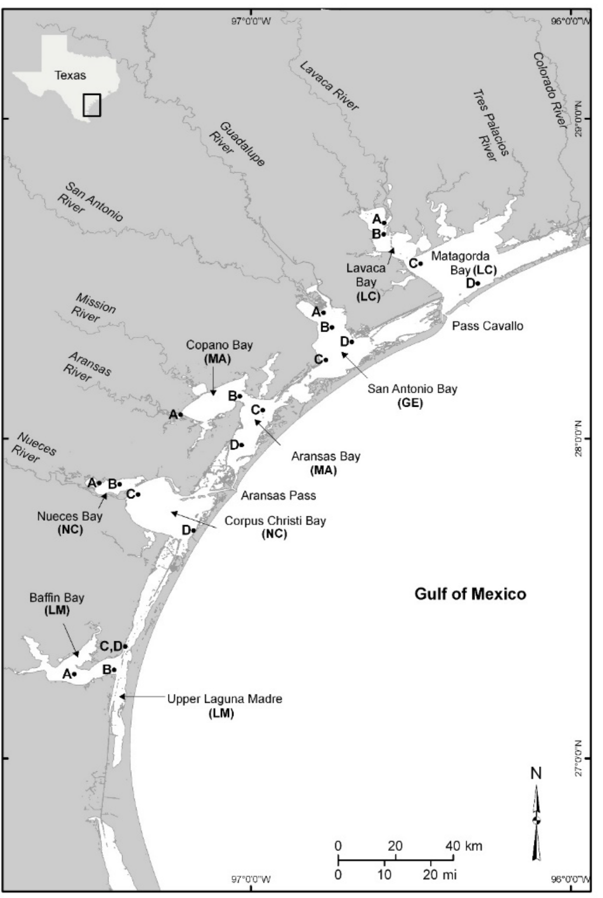
- The climatic gradient provides a perfect natural experiment replicated at the treatment level
  - 2 highly positive estuaries (SN and TSJ)
  - 2 positive estuaries (LC and GE)
  - 2 neutral estuaries (MA and NC)
  - 2 negative estuaries (UL and LL)

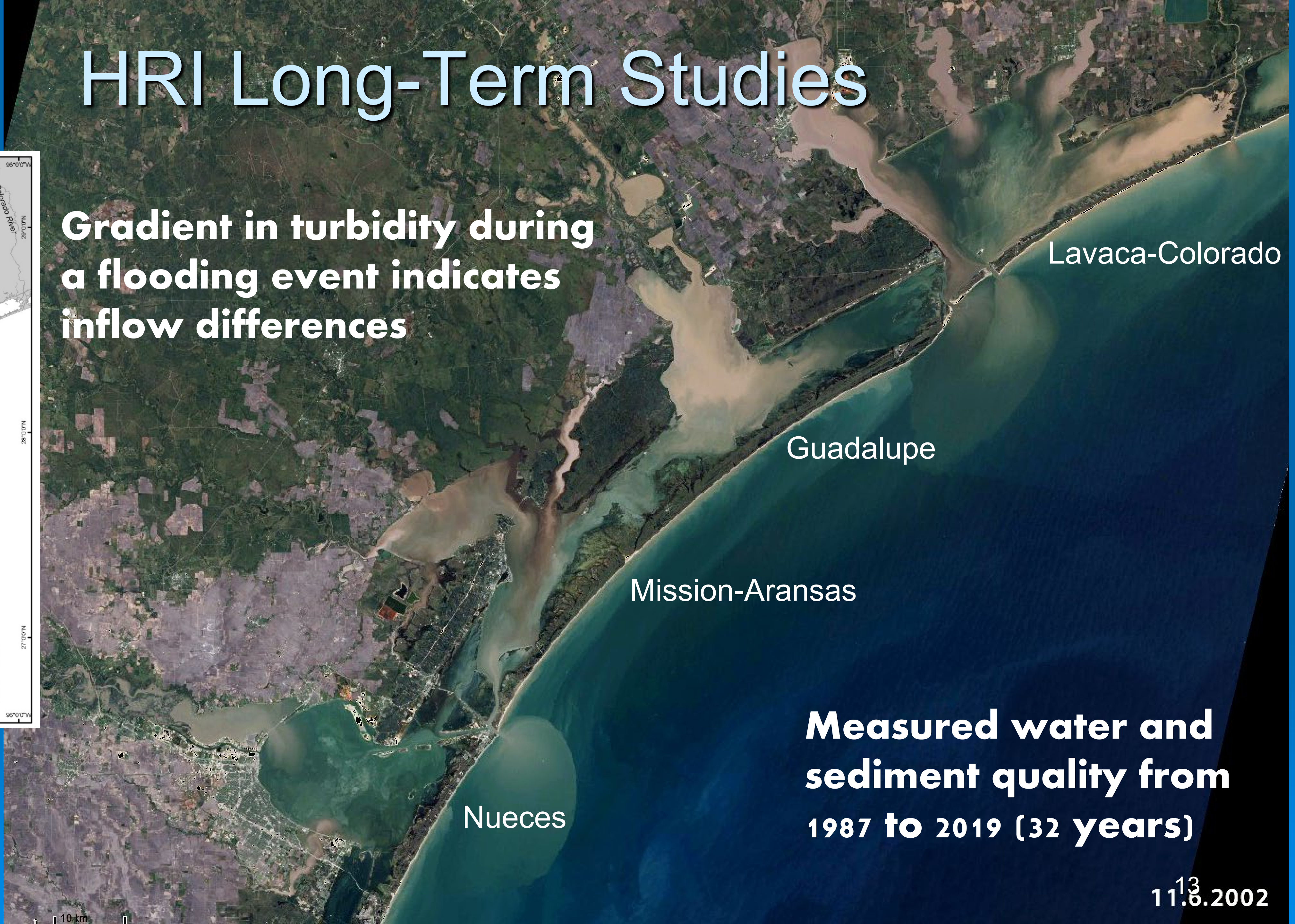
Inflow Balance (1000 ac-ft/month)



HRI Long-Term Studies

Gradient in turbidity during a flooding event indicates inflow differences





Measured water and sediment quality from 1987 to 2019 (32 years)

What Have We Learned in 30+ Years?

- Approach has evolved:
  - From direct to indirect effects on consumers
  - From species to ecosystem-based management
- There are now many quantitative tools:
  - Max-bin regression
  - Percent of flow approach
  - Productivity model
  - Community structure/salinity habitat model
  - Water quality models
  - Water quality coupled to flow models

What Have We Learned in 30+ Years?

- Inflow controls community structure and productivity
  - Salinity zones define estuary habitat
  - More flow means more community and functional diversity
  - Freshwater residence time drives process rates
- Management implications
  - Have developed quite a few products and tools
  - Community structure and functional groups change dramatic
  - Restoration works
  - Manage for refuges in upper parts of estuaries during droughts, i.e., small volumes matter

Current Texas Law: Senate Bill 3 (2007)

- Basin-specific Standards
- Science-based Environmental Flow Objectives
- Local Stakeholder Process to Balance Water Needs
- Certainty for Water Rights Permit Applicants
- Follow-up Adaptive Management on 10-year cycles

Senate Bill 3 Environmental Flow Players

- Environmental Flows Advisory Group (EFAG)
  - 3 Senate, 3 House, 3 heads of State Resource Agencies (TCEQ, TPWD, TWDB)
- Science Advisory Committee (SAC)
- ~~Basin and Bay Expert Science Teams (BBEST)~~
- Basin and Bay Area Stakeholder Committees (BBASC)
- TCEQ – Water Rights Regulatory Role

Legal Framework for Environmental Flow Standards

- Texas Water Code §§ 11.1471(a)(1), 11.147(e-3)
- Standards must be:
  - "**adequate**" to support a "**sound ecological environment**"
  - to the "**maximum extent reasonable**"
  - after considering "**other public interests and other relevant factors**"
- TCEQ must apply the environmental flow standards to develop the appropriate conditions for water rights permits.

Nueces River flowing into Nueces Bay

Some SB3 Regimes are Simple

TCEQ - Chapter 298b - Environmental Flow Standards for Galveston Bay System

Bay and Estuary Freshwater Inflow Standards for the Galveston Bay System

Basin	Annual Inflow Quantity (af)	Annual Target Frequency	Winter Inflow Quantity (af)	Winter Target Frequency	Spring Inflow Quantity (af)	Spring Target Frequency	Summer Inflow Quantity (af)	Summer Target Frequency	Fall Inflow Quantity (af)	Fall Target Frequency
Trinity	2,816,532	50%	500,000	40%	1,300,000	40%	245,000	40%	N/A	N/A
	2,245,644	60%	250,000	50%	750,000	50%	180,000	50%	N/A	N/A
	1,357,133	75%	160,000	60%	500,000	60%	75,000	60%	N/A	N/A
San Jacinto	1,460,424	50%	450,000	40%	500,000	40%	220,000	40%	200,000	40%
	1,164,408	60%	278,000	50%	290,000	50%	100,000	50%	150,000	50%
	703,699	75%	123,000	60%	155,000	60%	75,000	60%	90,000	60%

af = acre-feet

But Some SB3 Regimes are Complicated

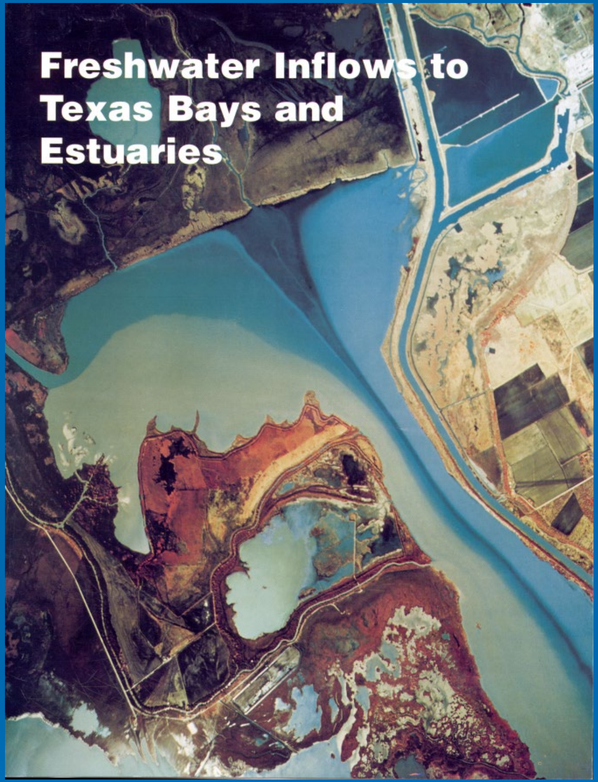
TCEQ - Chapter 298e - Environmental Flow Standards for San Antonio Bay System

Inflow Regime	Inflow Quantity (February) (af)	Inflow Quantity (March-May) (af)	Strategy Target Frequency
Spring 1	N/A	550,000-925,000	at least 12% of the years
Spring 2	N/A	375,000-550,000	at least 12% of the years
Spring 3	N/A	275,000-375,000	N/A
Spring 4	greater than 75,000	150,000-275,000	N/A
Spring 5	less than 75,000	150,000-275,000	N/A
Spring 6	N/A	0-150,000	no more than 9% of the years
Spring 2 and Spring 3 combined	N/A	N/A	at least 17% of the years
Spring 4 and Spring 5 combined	N/A	N/A	less than 67% of the total

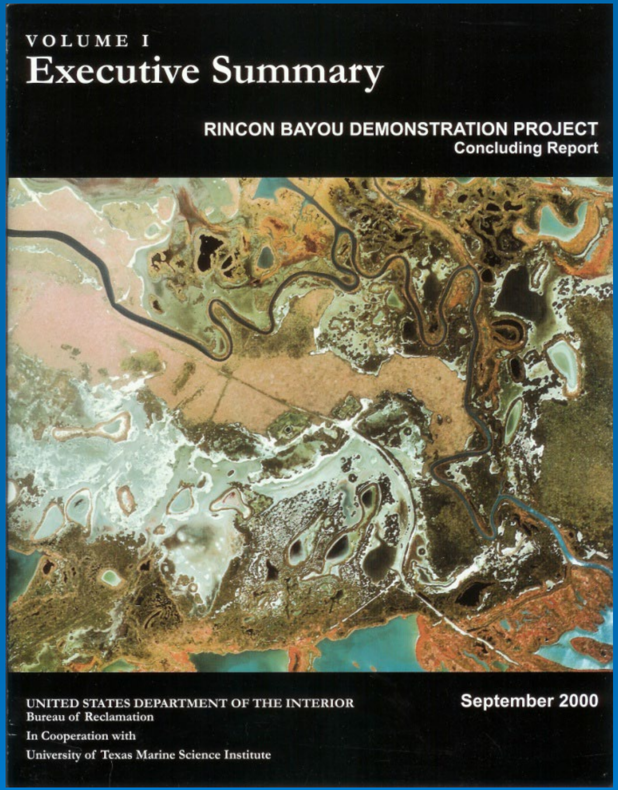
Inflow Regime	Inflow Quantity (June) (af)	Inflow Quantity (July-September) (af)	Strategy Target Frequency
Summer 1	N/A	450,000-800,000	at least 12% of the years
Summer 2	N/A	275,000-450,000	at least 17% of the years
Summer 3	N/A	170,000-275,000	N/A
Summer 4	greater than 40,000	75,000-170,000	N/A
Summer 5	less than 40,000	75,000-170,000	N/A
Summer 6	N/A	50,000-75,000	N/A
Summer 7	N/A	0-50,000	no more than 6% of the years
Summer 2 and Summer 3 combined	N/A	N/A	at least 30% of the years
Summer 4 and Summer 5 combined	N/A	N/A	Summer 5 no more than 17% of the

- But volumes are still large, and can be zero during droughts

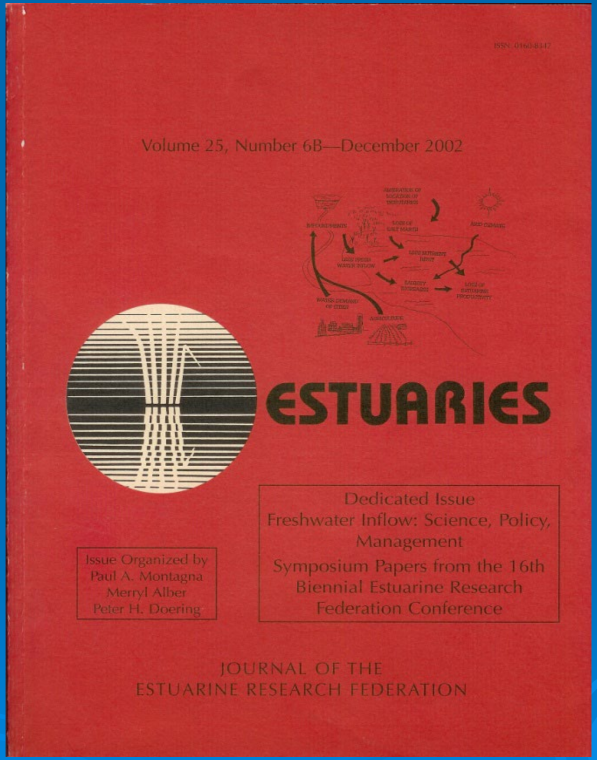
Previous Synthesis Efforts



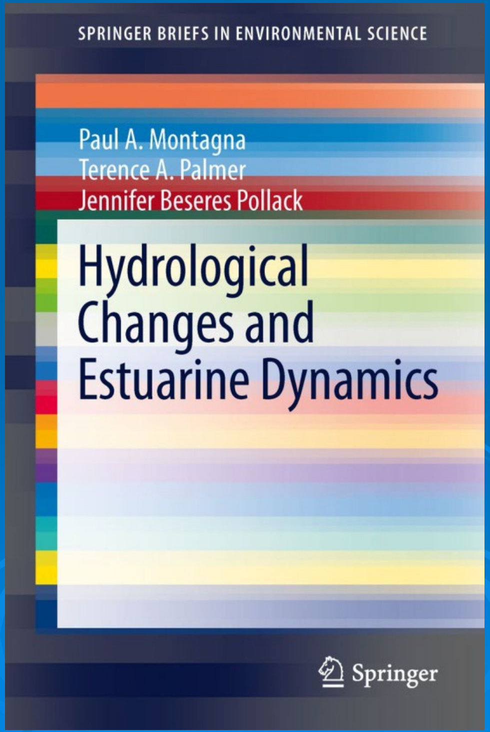
1995



2000



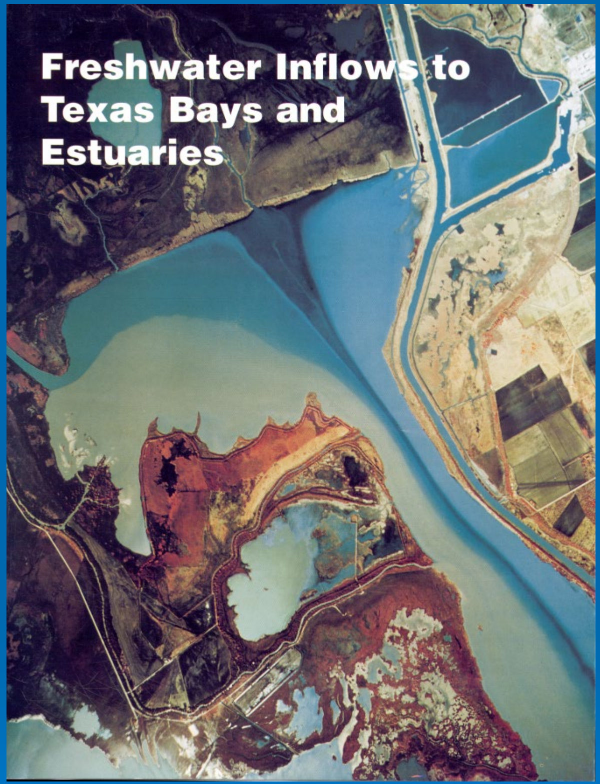
2002



2013

Need For a New Syntheis

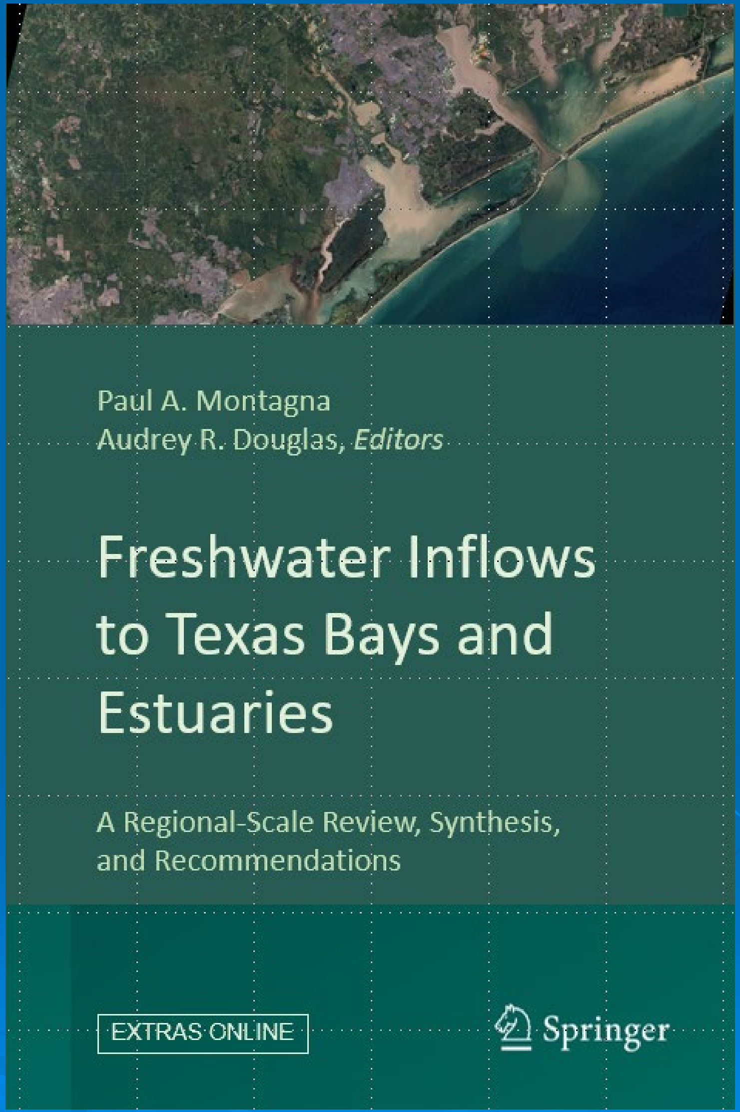
- Although published in 1995, latest data was from 1989
  - Lots of new data since 1989
- BBEST and BBASC reports since 2009
  - For every system
- Adaptive Management Studies since 2014



- It was time to put it all together!

Next Steps – Updated Synthesis

- Publish a new edition of "Freshwater Inflow to Texas Bays and Estuaries"
  - Legal framework is SB3, not HB2
  - Management goal now different
  - Methodology now different
  - 30 years of new data
  - Support adaptive management
  - Common, easily accessible historical data
  - Products that span beginners to experts
- Started April 2021, submitted Jan 2024



Cover Mock-up

Freshwater Inflow to Texas Bays & Estuaries

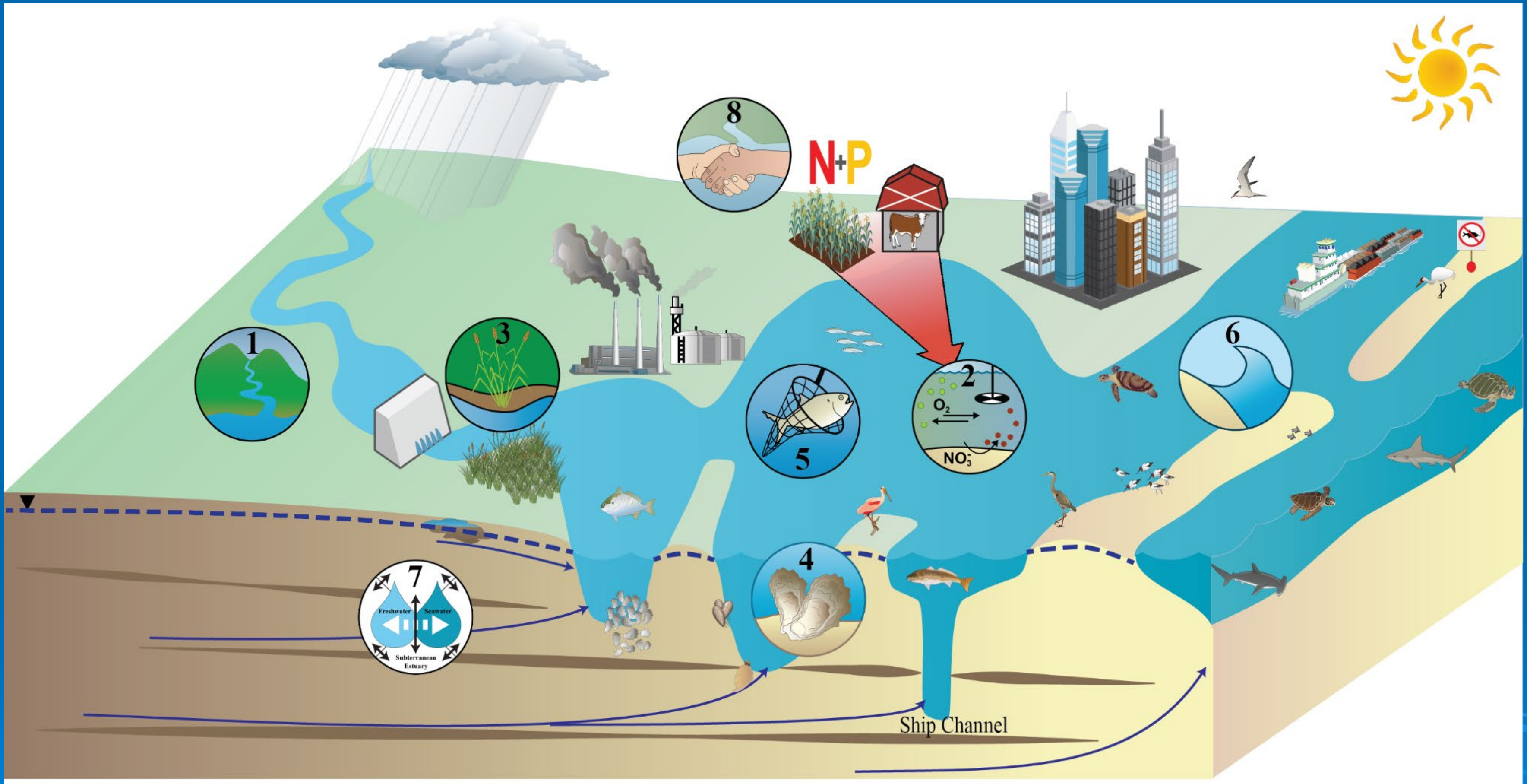
- 17+ chapters & 34 authors/co-authors:

  Preface/Foreword/Acknowledgements. P.A. Montagna

  1. Introduction - History of Inflow Studies in Texas. P. A. Montagna, W.L. Longley, E.A. Gomaa & J.C. Brown
  2. Historical Perspective and Context of Freshwater Inflow Policy and Law in Texas. Myron J. Hess
  3. Climate Effects on Inflows. J. Nielsen-Gammon & A.A. Tarter
  4. Hydrology, Circulation, and Salinity. D. Opdyke, J. Hoffmann, P.A. Montagna & J.F. Trungale
  5. Groundwater-Surface Water Interactions in the Coastal Zone. A.R. Douglas & D. Murgulet
  6. Influence of Inflows on Estuary Sediments. A.R. Douglas, P.A. Montagna & T. Dellapenna
  7. Nutrient-Phytoplankton Dynamics in Texas Estuaries. M.S. Wetz, L. Beecraft, M. McBride, J.L. Steichen & A. Quigg
  8. Physical and Biogeochemical Conditions and Trends in Texas Estuaries. X. Hu & H. Yin
  9. Coastal Wetland Habitats in Texas. J.C. Gibeaut, P.A. Montagna, J. Magolan & P. Huang.
  10. Submerged Aquatic Vegetation, Marshes, and Mangroves. K.A. Capistrant-Fossa, B.E. Batterton and K.H. Dunton
  11. Effect of Freshwater Inflow on Benthic Infauna. P.A. Montagna, R.D. Kalke & L.J. Hyde
  12. Effects of Climate-Driven Salinity Regimes on Oyster Disease Dynamics at Local and Regional Scales. K.B. Savage, T.A. Palmer, P.A. Montagna & J. Beseres Pollack
  13. Plankton Dynamics in Texas Estuaries. A. Quigg, J.L. Steichen, L. Beecraft & M.S. Wetz
  14. Nekton and Mobile Epibenthos. D.M. Coffey, G.W. Stunz & P.A. Montagna
  15. Nitrogen and Phosphorous Budgets for Texas Estuaries. D.A. Marshall & P.A. Montagna
  16. Social and Economic Values of Environmental Flows to the Coast. D.W. Yoskowitz
  17. Summary of Recommendations for the Future. P.A. Montagna & A.R. Douglas

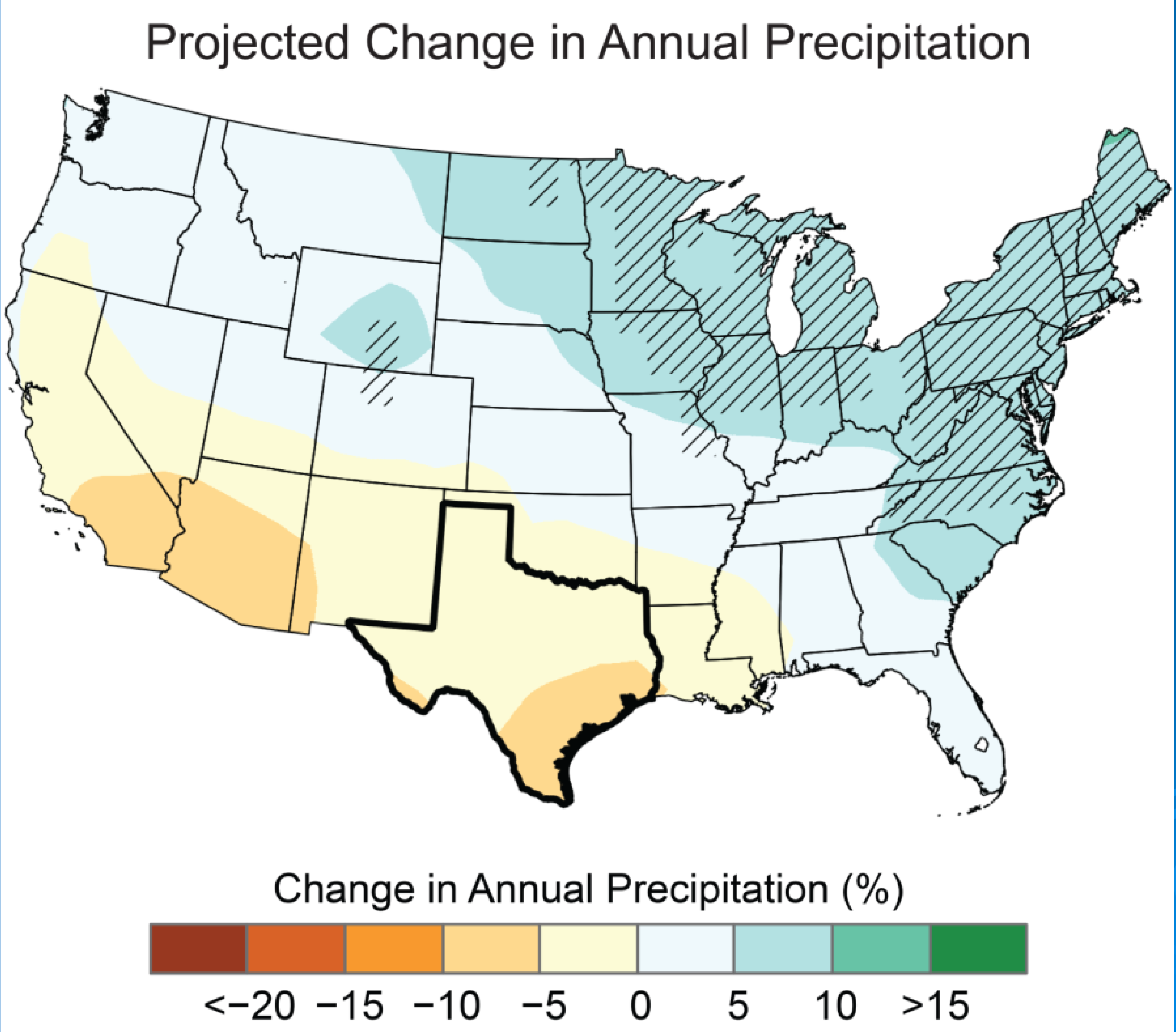
- Extras: Online supplements, data, and documents.
- StoryMap

Chapters



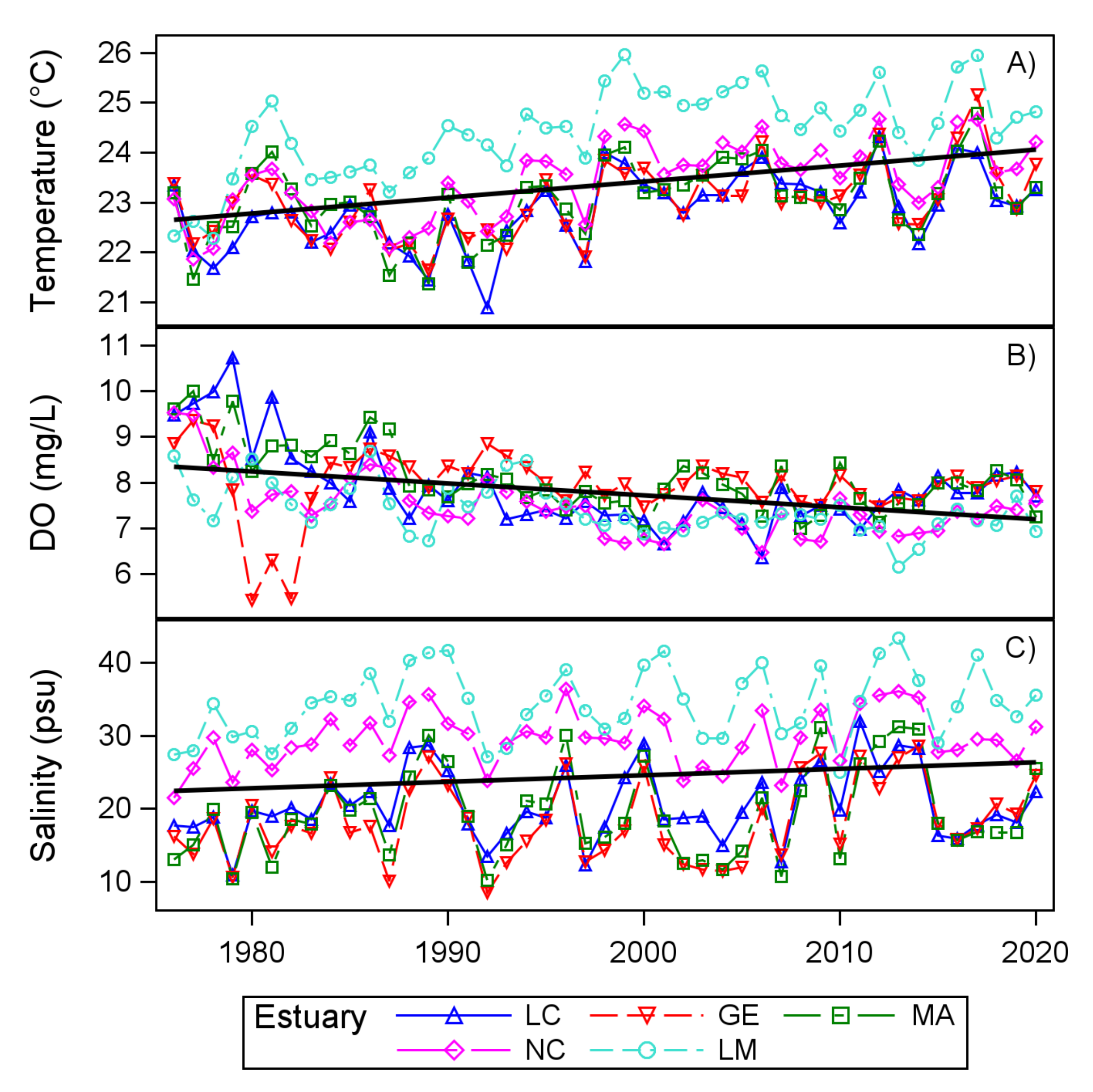
1 Hydrology
2 Nutrients & Plankton
3 Wetland Habitats
4 Benthic Habitats
5 Fish & Nekton
6 Tide & Circulation
7 Sediments & Groundwater
8 Environmental Flow Law & Regulations

Chapters



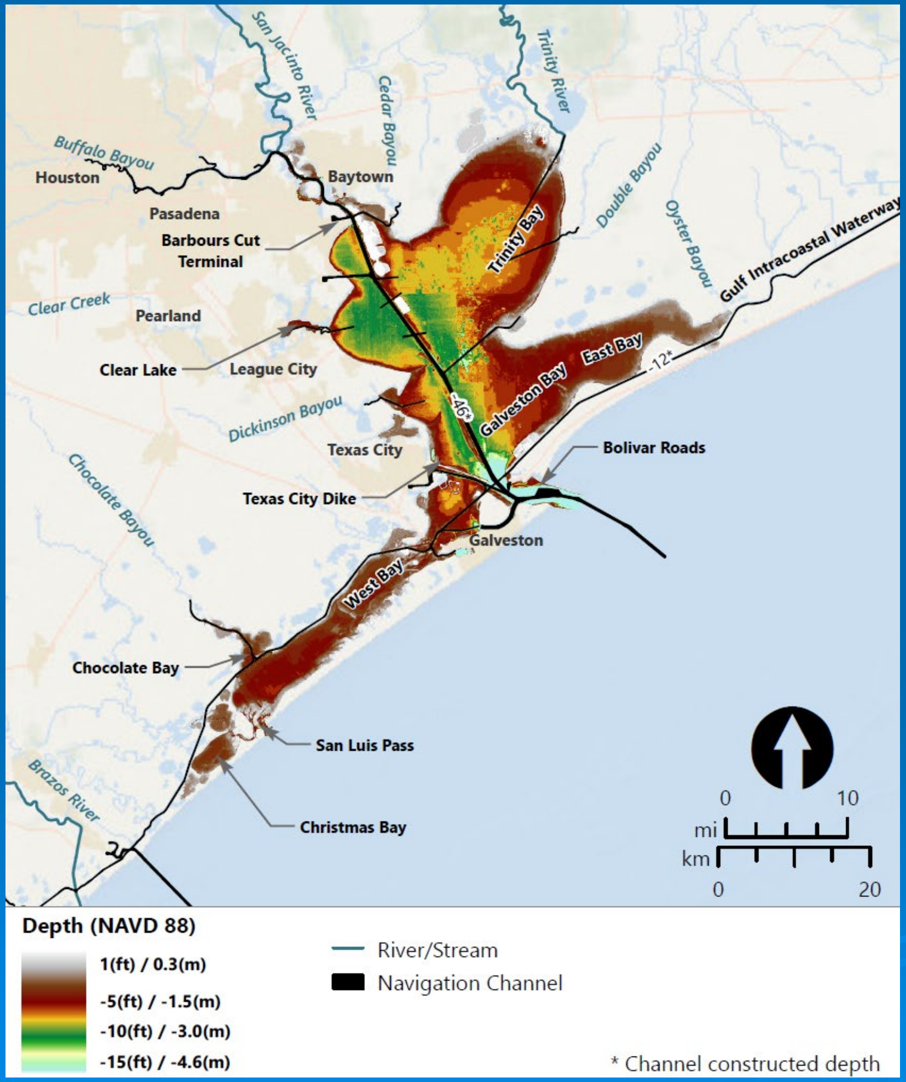
Projected Change in Annual Precipitation
Change in Annual Precipitation (%)
<−20 −15 −10 −5 0 5 10 >15

Chapters

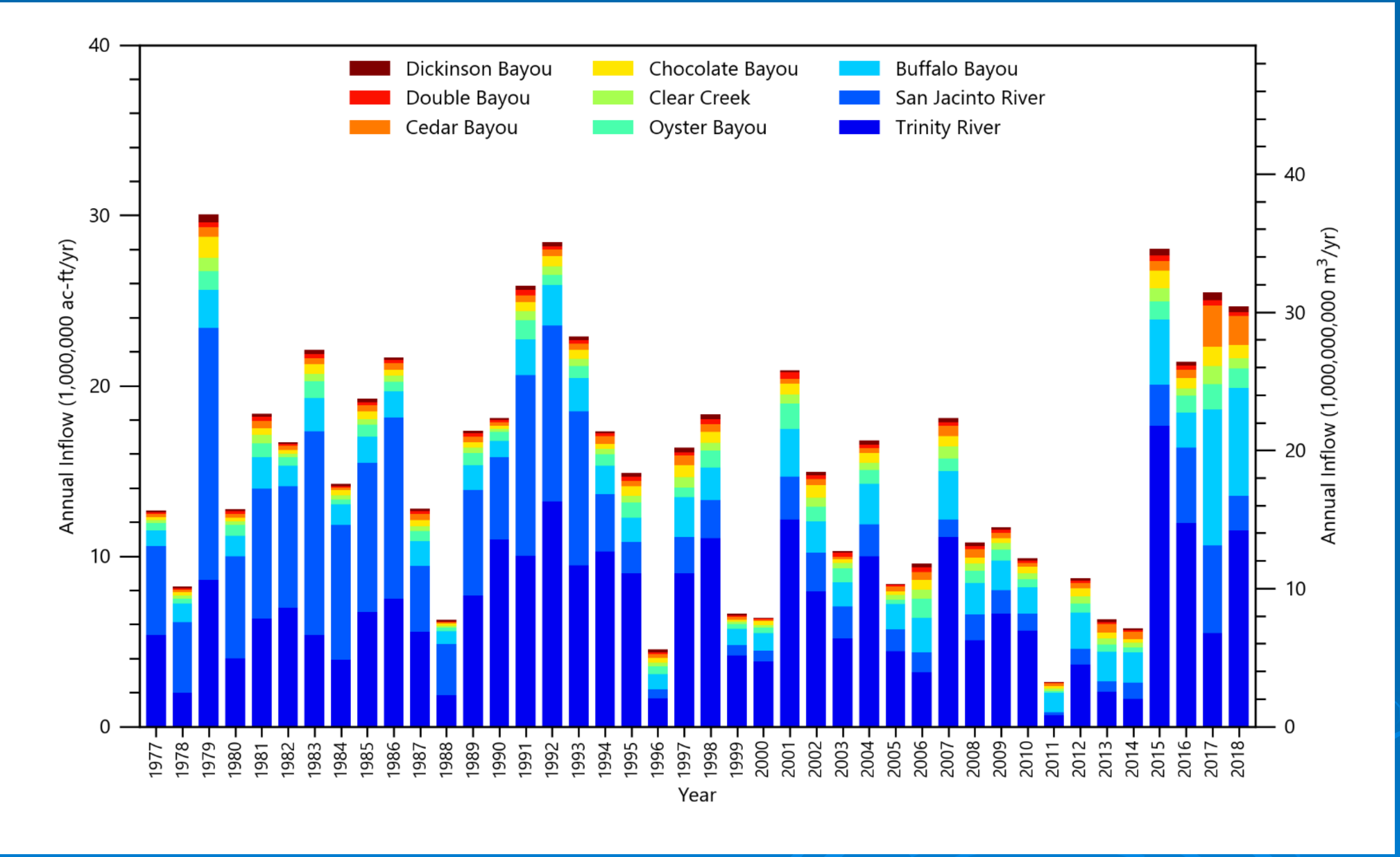


Temperature (°C)
26
25
24
23
22
21
A)
DO (mg/L)
11
10
9
8
7
6
B)
Salinity (psu)
40
30
20
10
C)
1980
1990
2000
2010
2020
Estuary
LC
GE
MA
NC
LM

Chapters

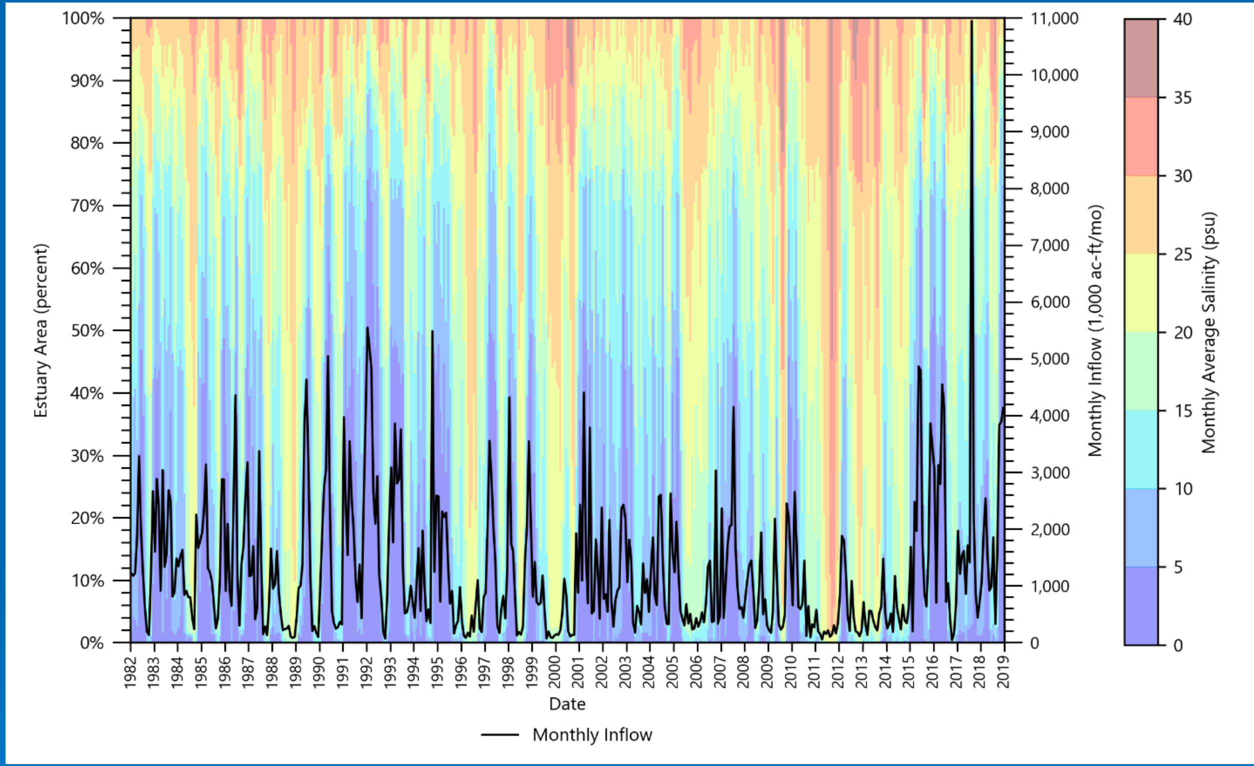


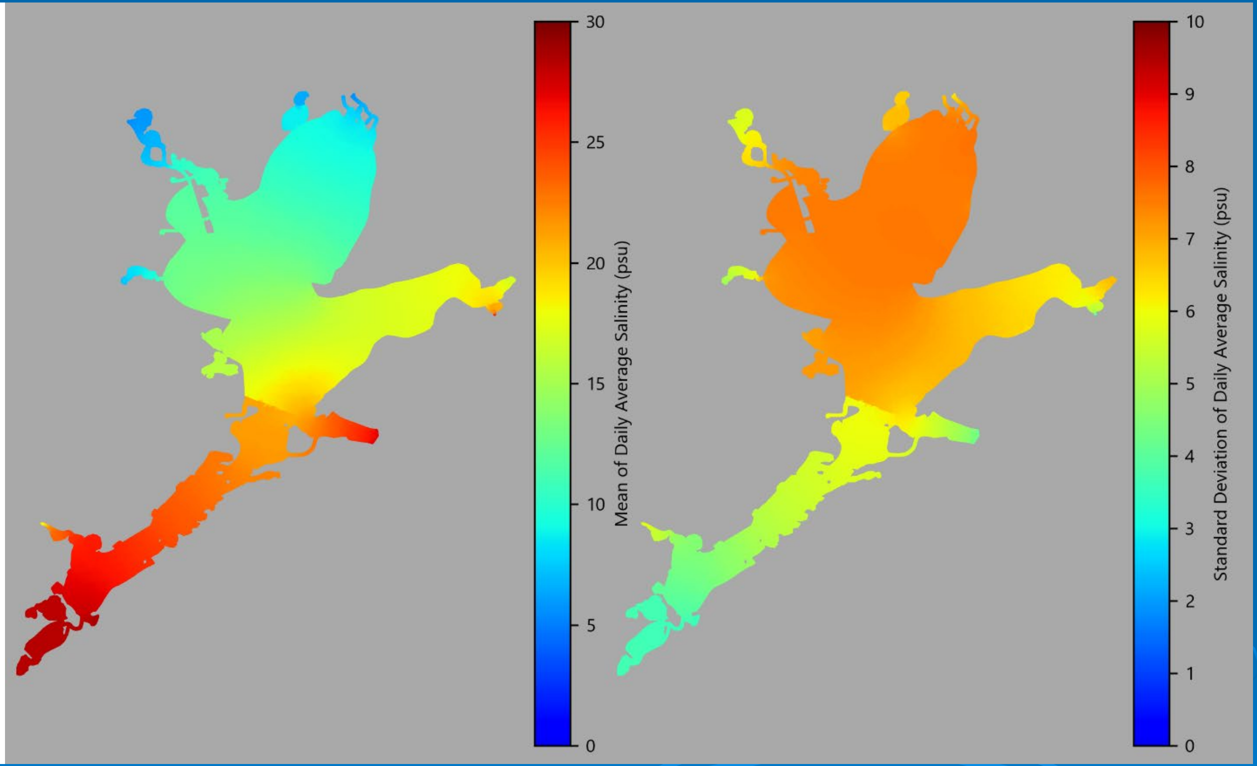
San Jacinto River
Trinity River
Cedar Bayou
Buffalo Bayou
Houston
Baytown
Pasadena
Barbours Cut Terminal
Trinity Bay
Double Bayou
Oyster Bayou
Gulf Intracoastal Waterway
Clear Creek
Pearland
Clear Lake
League City
East Bay
Galveston Bay
Dickinson Bayou
Texas City
Bolivar Roads
Chocolate Bayou
Texas City Dike
Galveston
West Bay
Chocolate Bay
San Luis Pass
Brazos River
Christmas Bay
Depth (NAVD 88)
1(ft) / 0.3(m)
-5(ft) / -1.5(m)
-10(ft) / -3.0(m)
-15(ft) / -4.6(m)
River/Stream
Navigation Channel
* Channel constructed depth



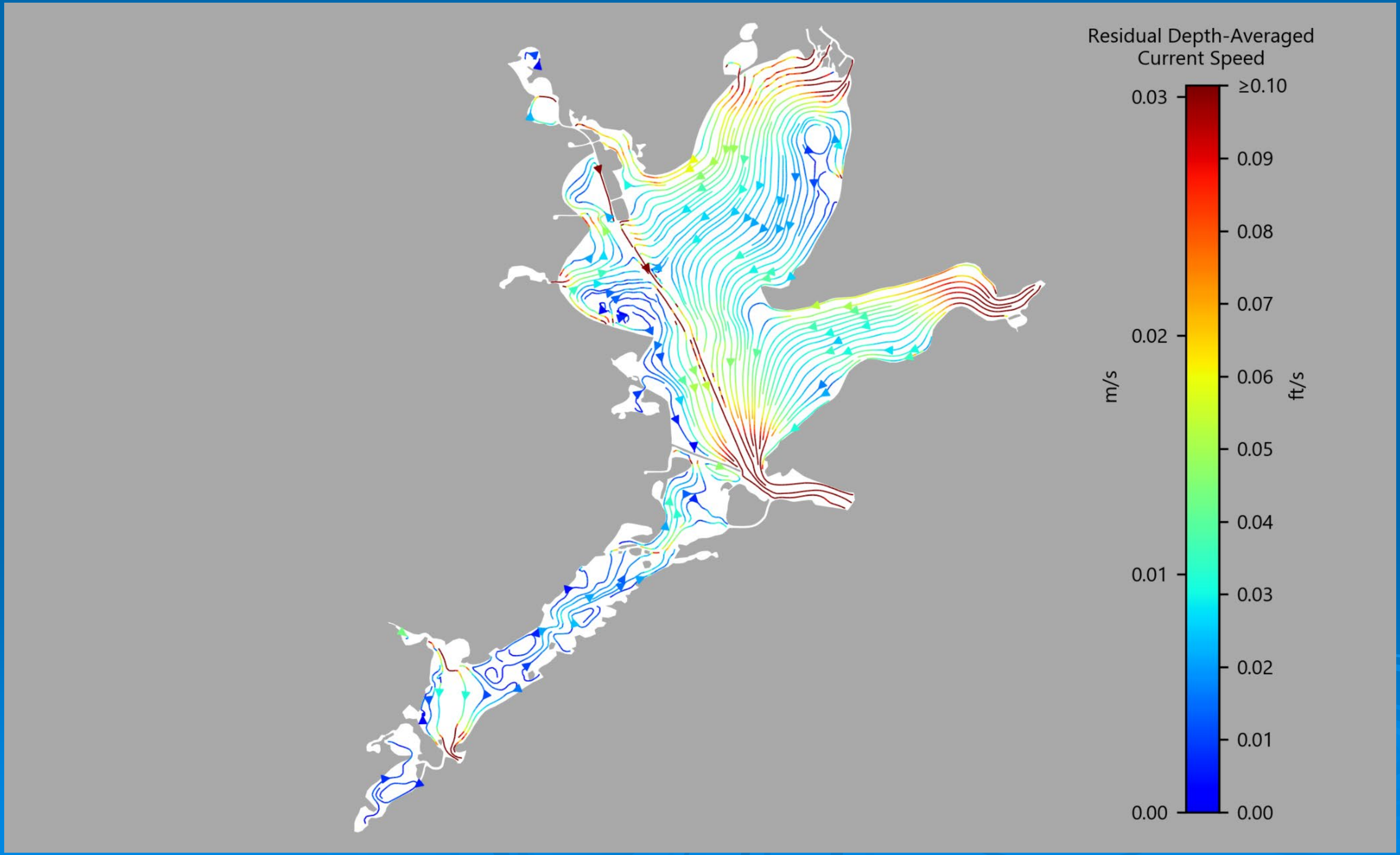
Dickinson Bayou
Double Bayou
Cedar Bayou
Chocolate Bayou
Clear Creek
Oyster Bayou
Buffalo Bayou
San Jacinto River
Trinity River
Annual Inflow (1,000,000 ac-ft/yr)
Annual Inflow (1,000,000,000 m³/yr)
Year

Chapters


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Estuary Area (percent)
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Monthly Inflow (1,000 ac-ft/mo)
40
35
30
25
20
15
10
5
0
Monthly Average Salinity (psu)
1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019
Date
Monthly Inflow


30
25
20
15
10
5
0
Mean of Daily Average Salinity (psu)
10
9
8
7
6
5
4
3
2
1
0
Standard Deviation of Daily Average Salinity (psu)

Chapters



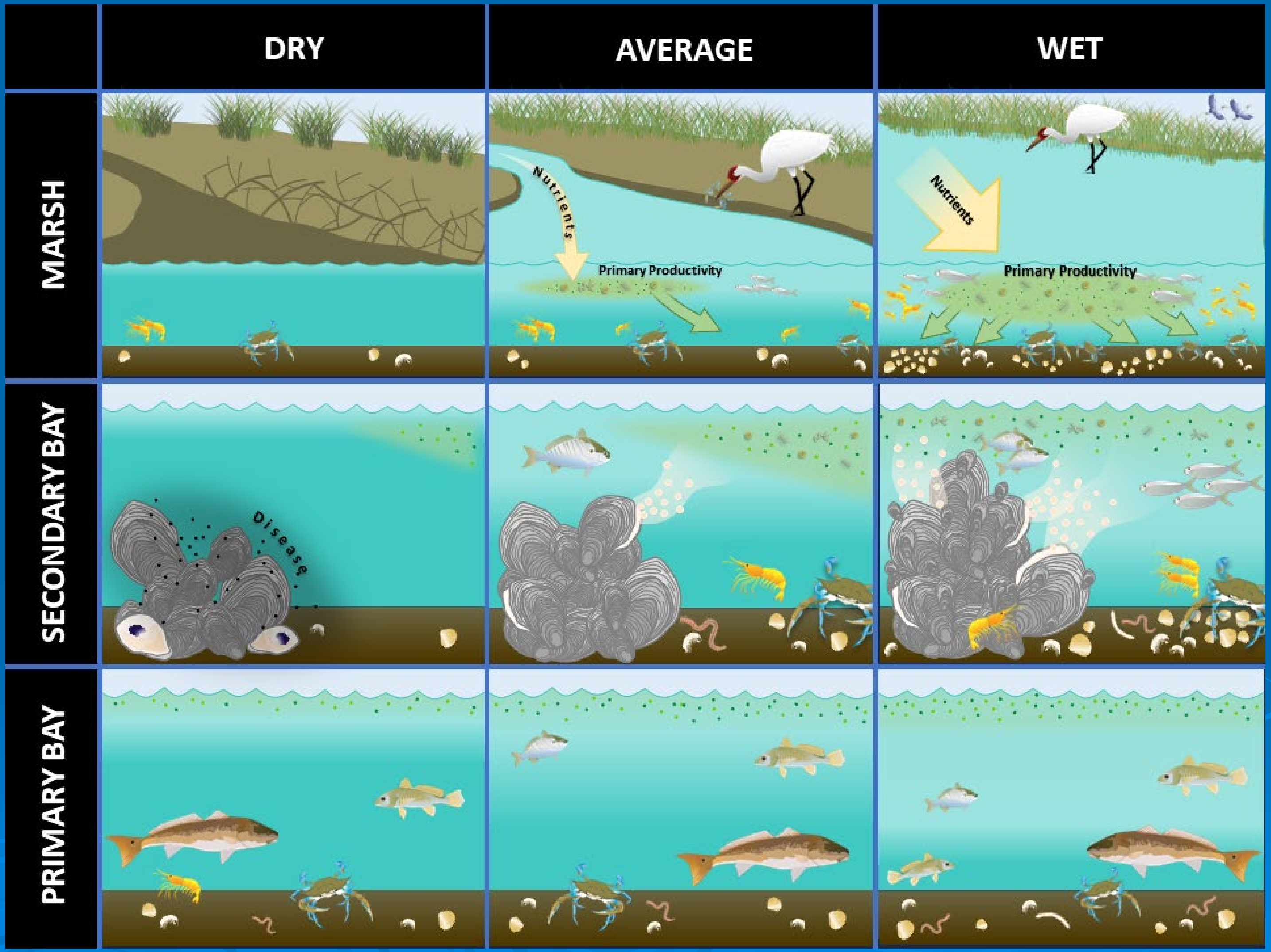
Residual Depth-Averaged
Current Speed
m/s
ft/s
0.03
0.02
0.01
0.00
≥0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00

Conclusions

- There is a lot of data, but little is focused to define estuary responses to inflow that connects physical characteristics and biological responses
  - State-wide monitoring approach is needed
- 3-D physics-based models of circulation needed
  - Updated bathymetry, shoreline locations, and salinity monitoring to calibrate and validate the models
- Mechanistic studies needed to link biological response to physical dynamics
- Because of the semi-arid climate, there may never be enough water to dilute salinity in all bay systems, especially in central and south Texas, so focused flows protect key nursery habitats during droughts is needed
- Some FWI standards are complex, using complex hydrology tables
  - A simpler, standard, approach is needed
  - Should be linked to biological outcomes, not just hydrology

Conclusions

- Everything is fine during average and wet periods, droughts are the problem



Better Outcomes Are Possible

- Focused flows to sustain natural nurseries during droughts
  - If the nursery function is protected, the bay will repopulate when it rains again
  - Smaller volumes of the bays need protection, so lower volumes of environmental water is needed

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Texas Water Journal
Volume 12, Number 1, September 27, 2021
Pages 129-139

Focused Flows to Maintain Natural Nursery Habitats

Paul A. Montagna[1*], Larry McKinney[1], David Yoskowitz[1]

https://doi.org/10.21423/twj.v12i1.7123

ArcGIS StoryMap

- Web-based application to share maps in the context of narrative text and other multimedia content
- Under development, will be asking folks to review it soon
  - https://storymaps.arcgis.com/collections/88ebe5b53085412e8a2d385e34e98ab9
  - Maps, tables, figures, oral histories
  - Authors: Michelle Culver, Dan Opdyke, Audrey Douglas, Paul Montagna, and Elani Morgan.

Collection

Freshwater Inflows to Texas Bays and Estuaries

A Regional-Scale Review, Synthesis, and Recommendations

Editors: Paul A. Montagna • Audrey R. Douglas

Get started

This Story Map presents an overview of the content from the book Freshwater Inflows to Texas Bays and Estuaries, A Regional-Scale Review, Synthesis, and Recommendations. Story Map authors: Michelle Culver, Dan Opdyke, Audrey Douglas, Paul Montagna, and Elani Morgan.

Acknowledgements:

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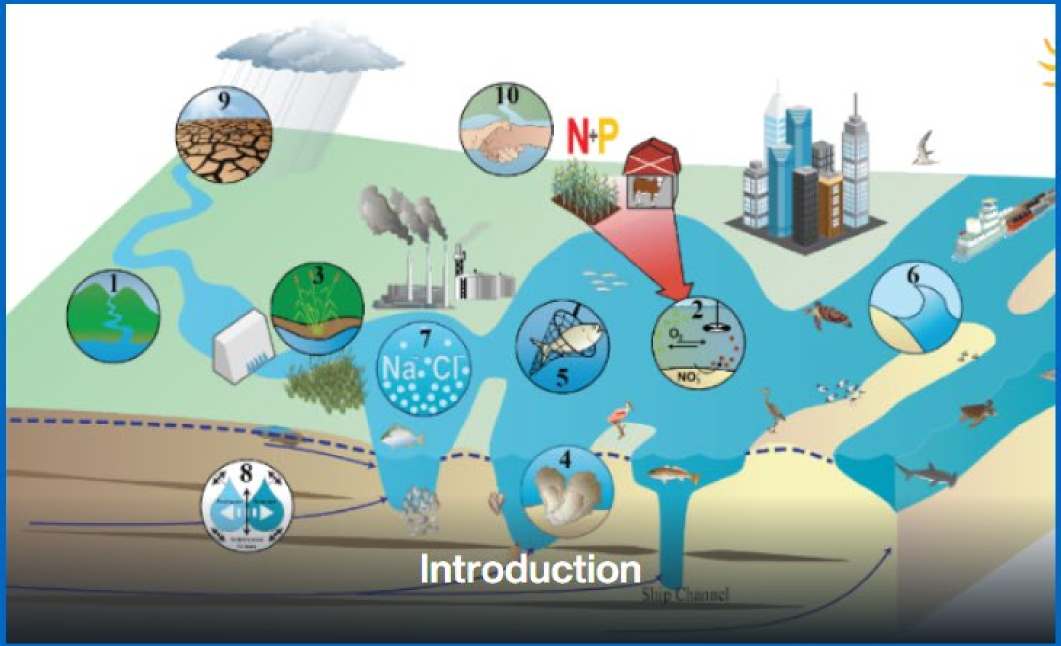
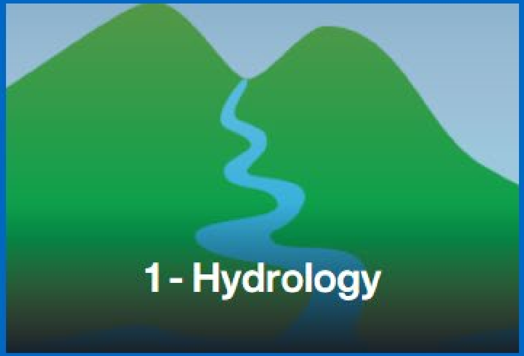
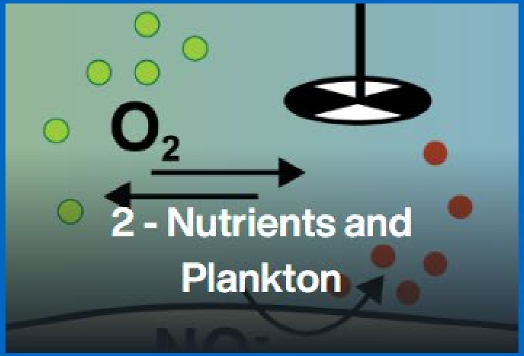






With Help From Many (over many years)

- Sponsors (past and present)
  - Local
    - City of Corpus Christi
    - Coastal Bend Bays & Estuaries Program
    - Lower Colorado River Authority
    - Matagorda Bay Foundation (Today)
  - State
    - TX Water Development Board (Today)
    - TX General Land Office (Today)
    - TX Sea Grant
  - Federal
    - National Aeronautics and Space Administration
    - National Oceanic Atmospheric Administration (Today)
    - National Science Foundation
    - US Army Corps of Engineers
    - US Bureau of Reclamation
  - Foundations
    - Harte RF, CF
    - Tinker
    - Hershey (Today)
    - Mitchell
    - National Fish and Wildlife Foundation

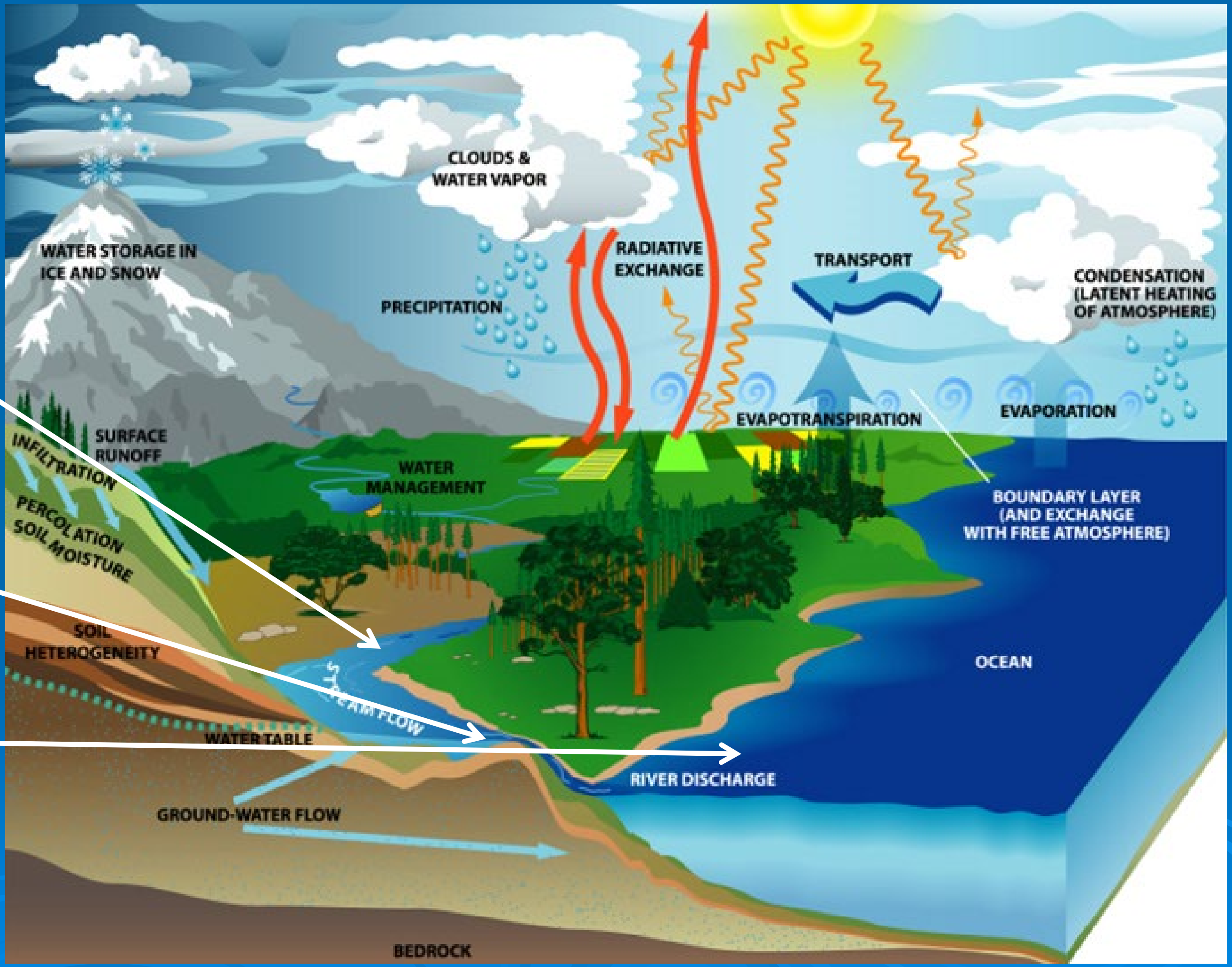
- Staff
  - Rick Kalke
  - Larry Hyde
  - +16 others
- 44 Students
- 15 Postdocs


Questions?
11.6.2002
10 km

Defining Environmental Flow

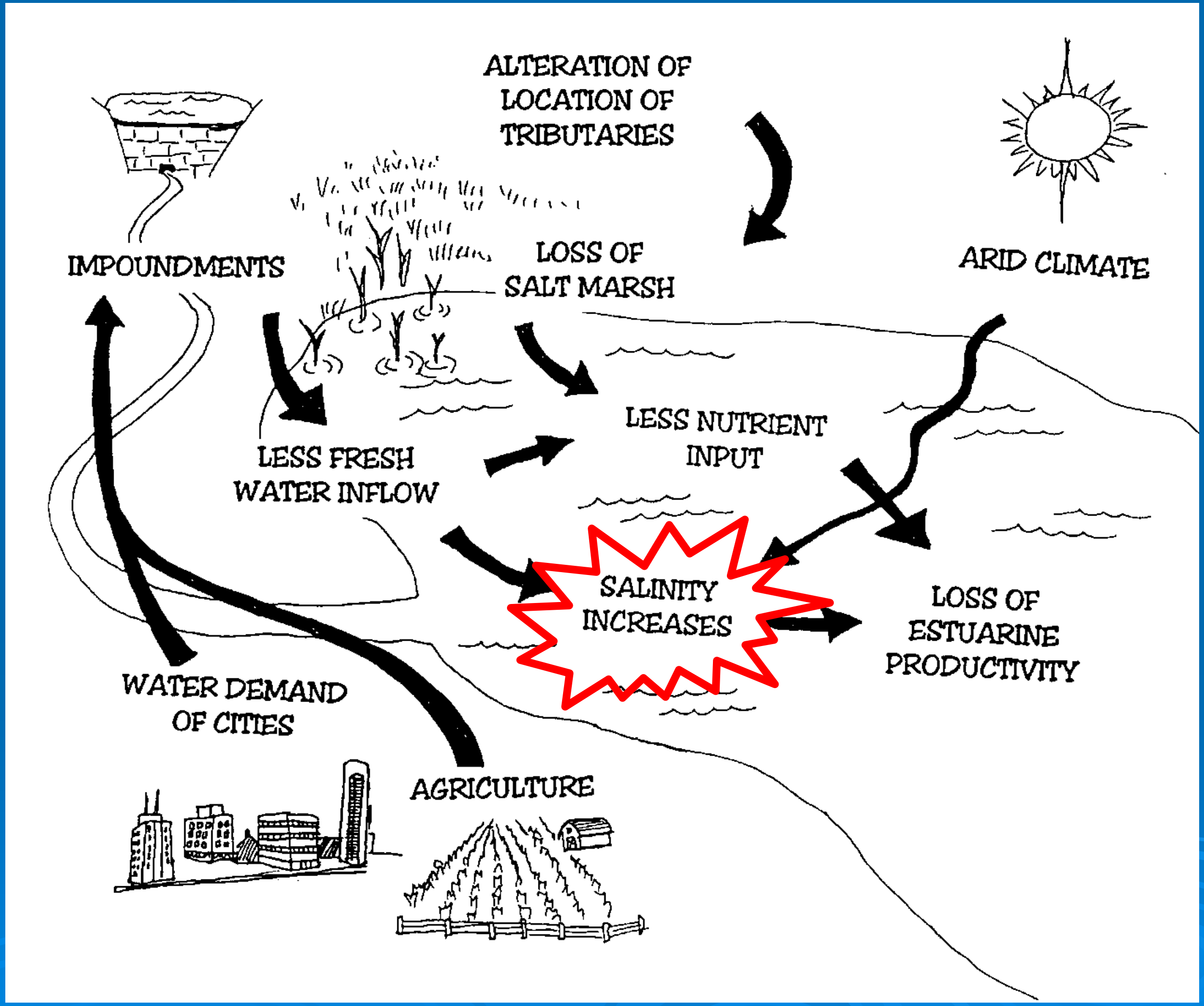
Definitions

- Instream: flow within streams and rivers
- Inflow: from rivers to estuaries
- Outflow: from estuaries to the coastal ocean



Altered Freshwater Inflow Changes Coastal Bays & Estuaries

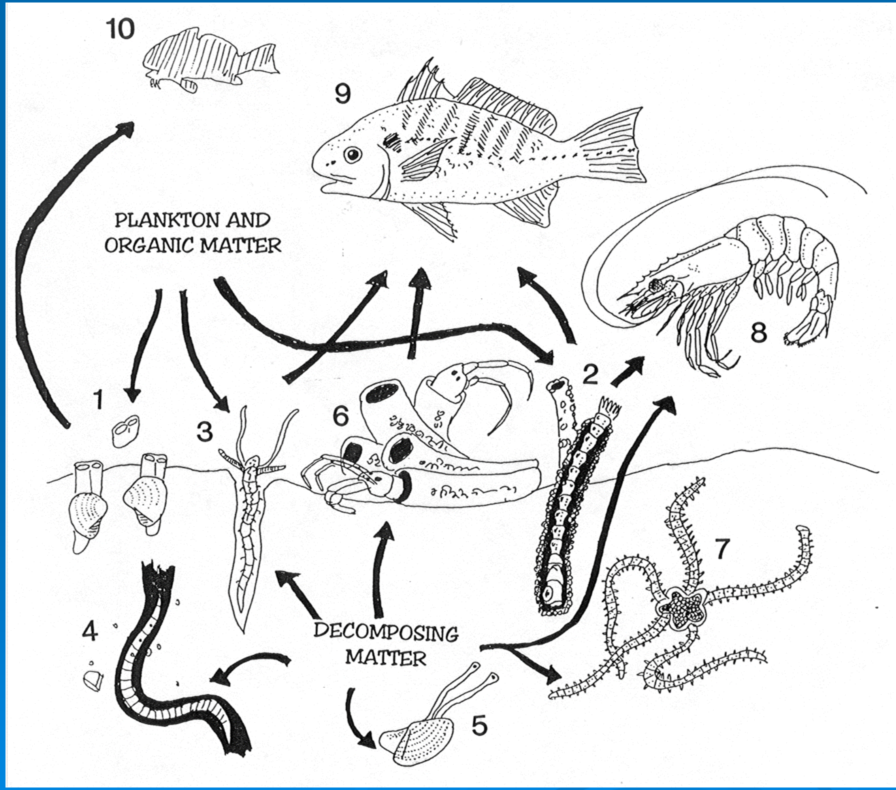
- Changes:
  - Hydrology
  - Nutrients
  - Sediments
  - Salinity
- Loses:
  - Habitat
  - Biodiversity
  - Productivity
  - Ecosystem Services



Source: Montagna et al. 1996, CCBNEP #8
http://cbbep.org/publications/virtuallibrary/ccbnep08.pdf

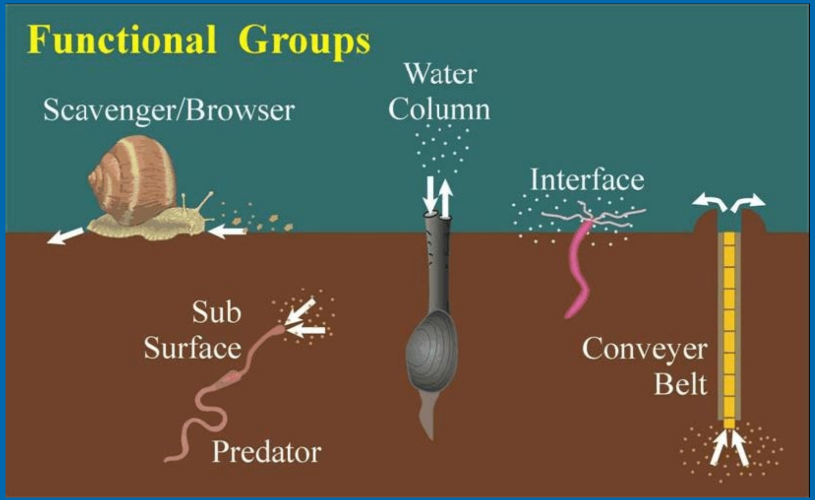
The Benthic Effect

- The bottom regulates or modifies most physical, chemical, geological and biological processes



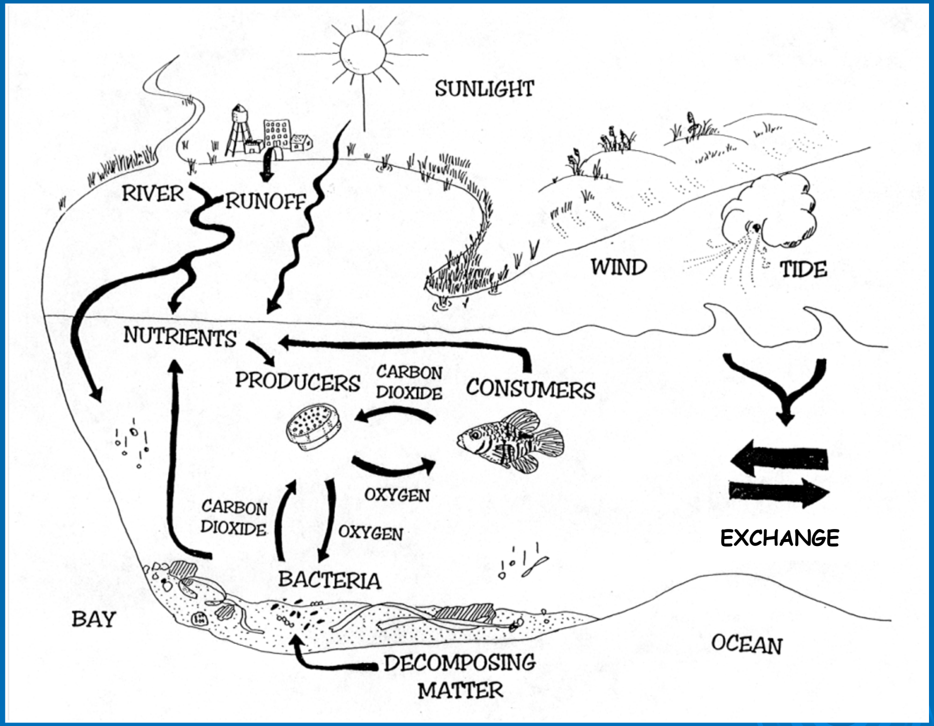
Source: Montagna et al. 1996, CCBNEP #8
http://cbbep.org/publications/virtuallibrary/ccbnep08.pdf

Benthos are Indicators and Integrators



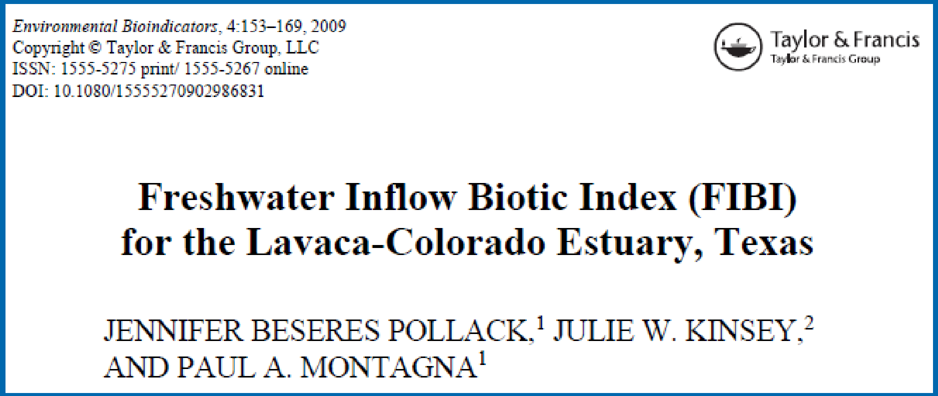
Source: Tenore, K.R. et al. (2006) *Journal of Experimental Marine Biology and Ecology* 300:392-402

- Sediments are the memory of the ecosystem
- Benthos are sampling water column 24/7/365
- Thus, benthos are integrators:
  - overlying water column is dynamic
  - benthos sample and integrate ephemeral events over long times scales



Source: Montagna et al. (1996) CCBNEP #8
http://cbbep.org/publications/virtuallibrary/ccbnep08.pdf

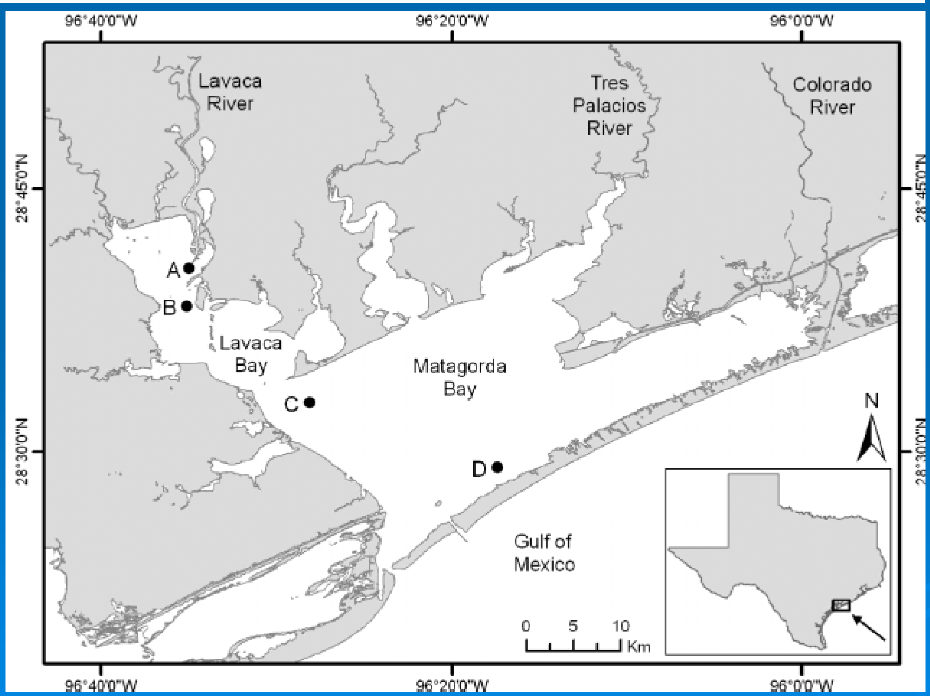
Key Findings Over 30 Years - Water


Environmental Bioindicators, 4:153–169, 2009

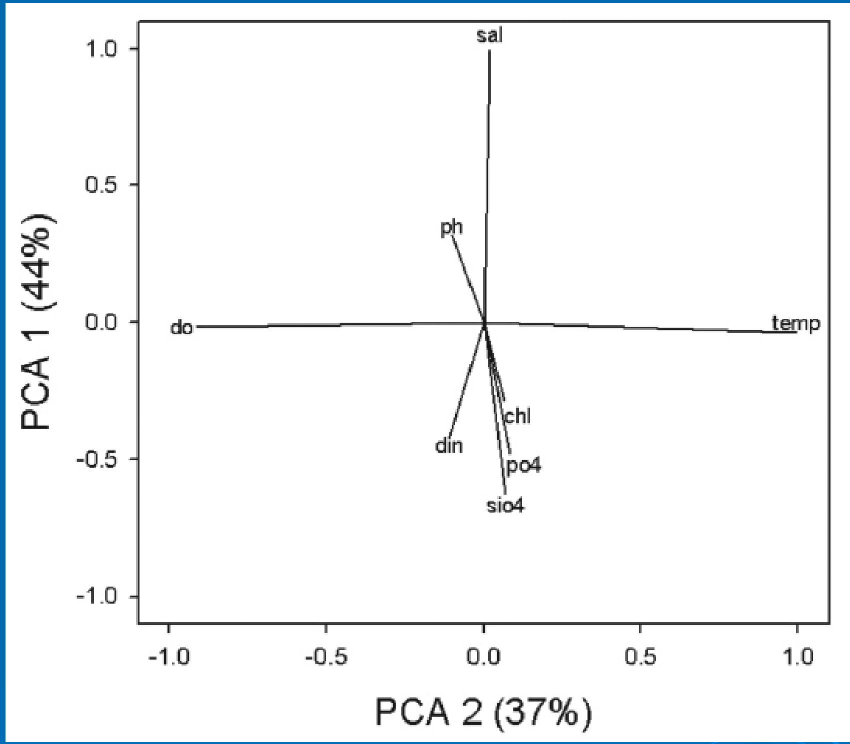
ISSN: 1555-5275 print/ 1555-5267 online
DOI: 10.1080/15555270902986831

Freshwater Inflow Biotic Index (FIBI) for the Lavaca-Colorado Estuary, Texas

JENNIFER BESERES POLLACK,[1] JULIE W. KINSEY,[2] AND PAUL A. MONTAGNA[1]

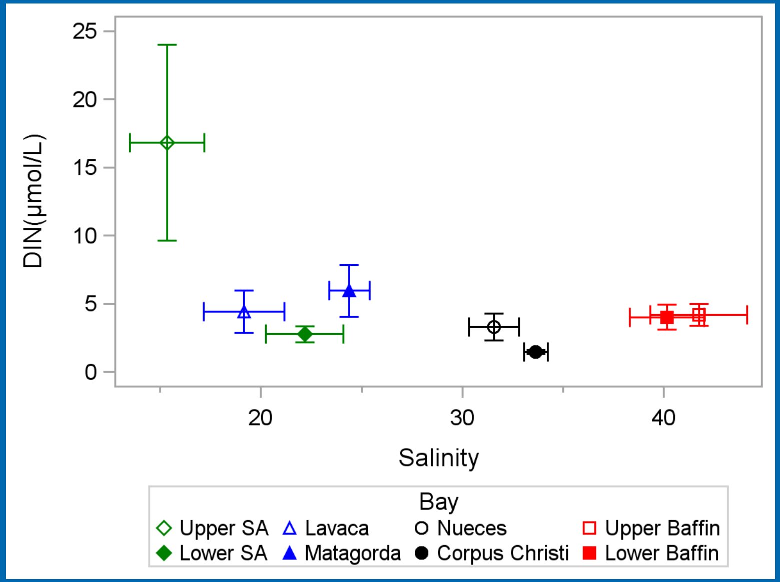


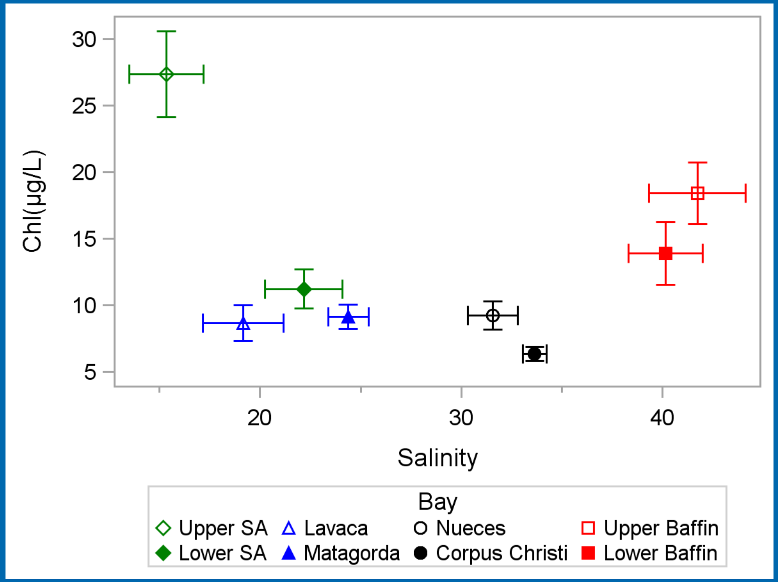
- Multivariate analysis based on correlation
- FWI = Salinity inversely correlated to nutrients & Chl
- Seasons = Temperature inversely related to DO

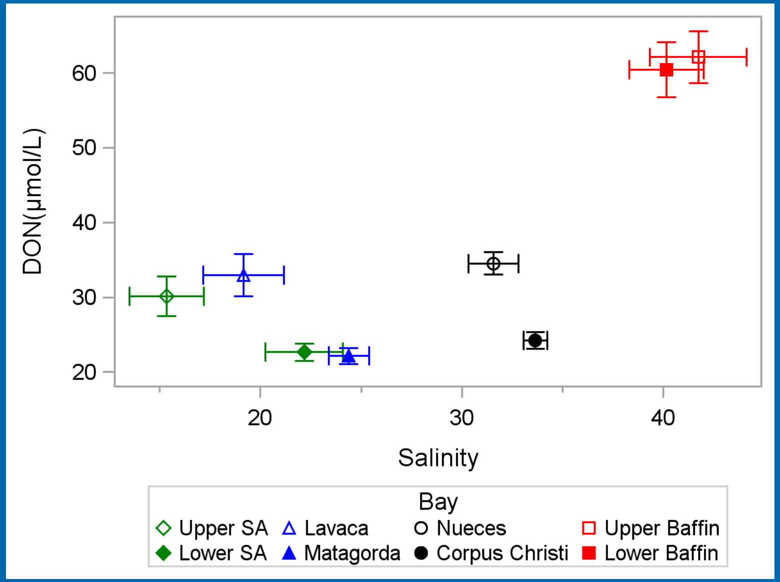


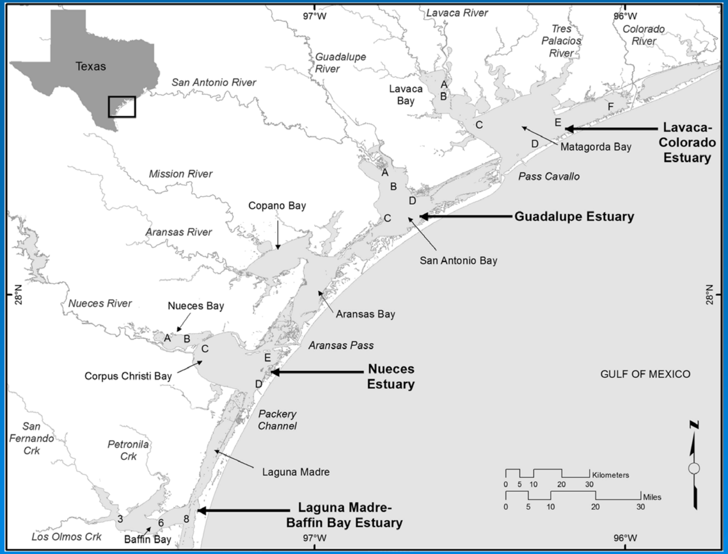
sal=Salinity, DIN=Dissolved Inorganic Nitrogen, po4=Phosphate, sio4=Silicate, chl=Chlorophyll, do=dissolved oxygen, temp=temperature

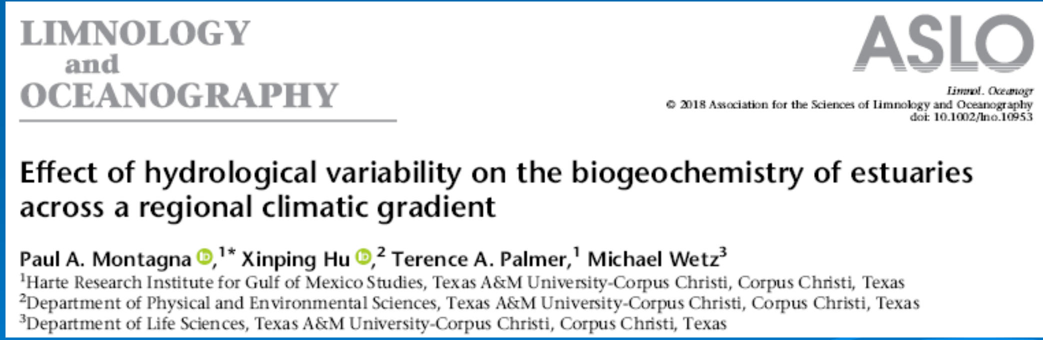
Key Findings Over 30 Years - Water











LIMNOLOGY and OCEANOGRAPHY

ASLO

Limnol. Oceanogr

doi: 10.1002/lno.10953

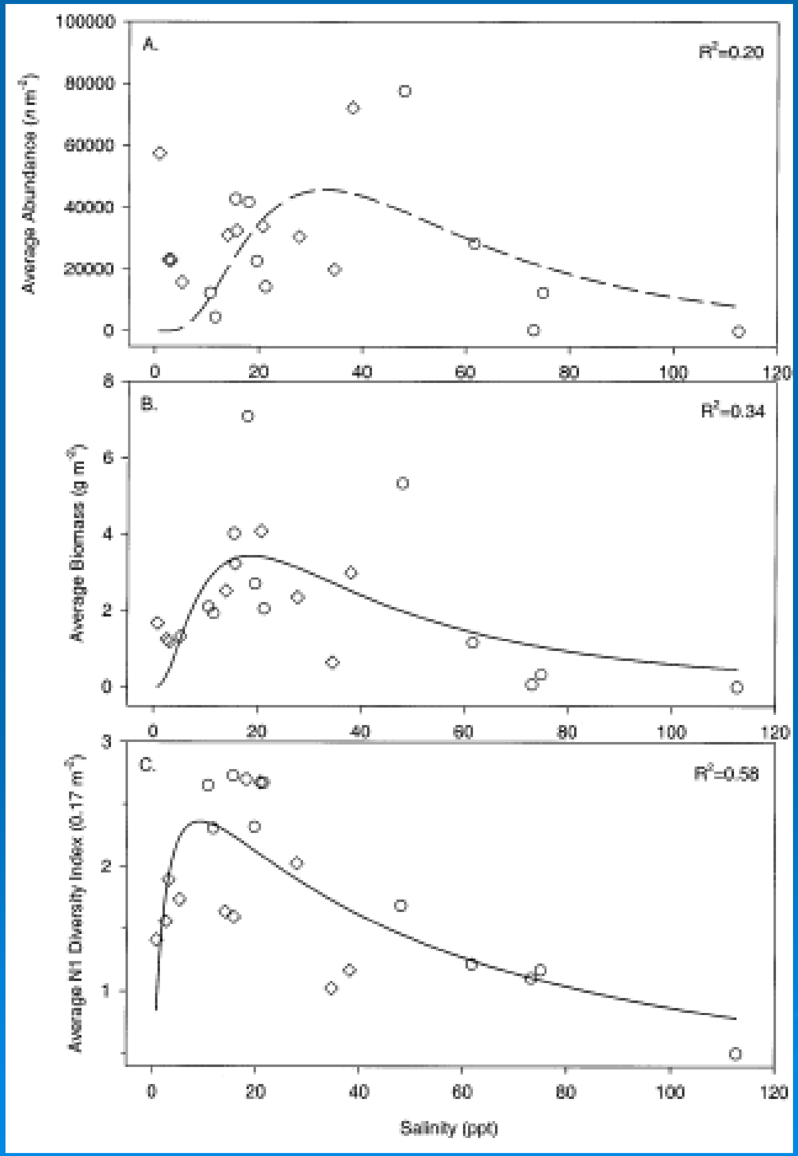
Effect of hydrological variability on the biogeochemistry of estuaries across a regional climatic gradient

Paul A. Montagna,[1]* Xinping Hu,[2] Terence A. Palmer,[1] Michael Wetz[3]

[1]Harte Research Institute for Gulf of Mexico Studies, Texas A&M University-Corpus Christi, Corpus Christi, Texas
[2]Department of Physical and Environmental Sciences, Texas A&M University-Corpus Christi, Corpus Christi, Texas
[3]Department of Life Sciences, Texas A&M University-Corpus Christi, Corpus Christi, Texas

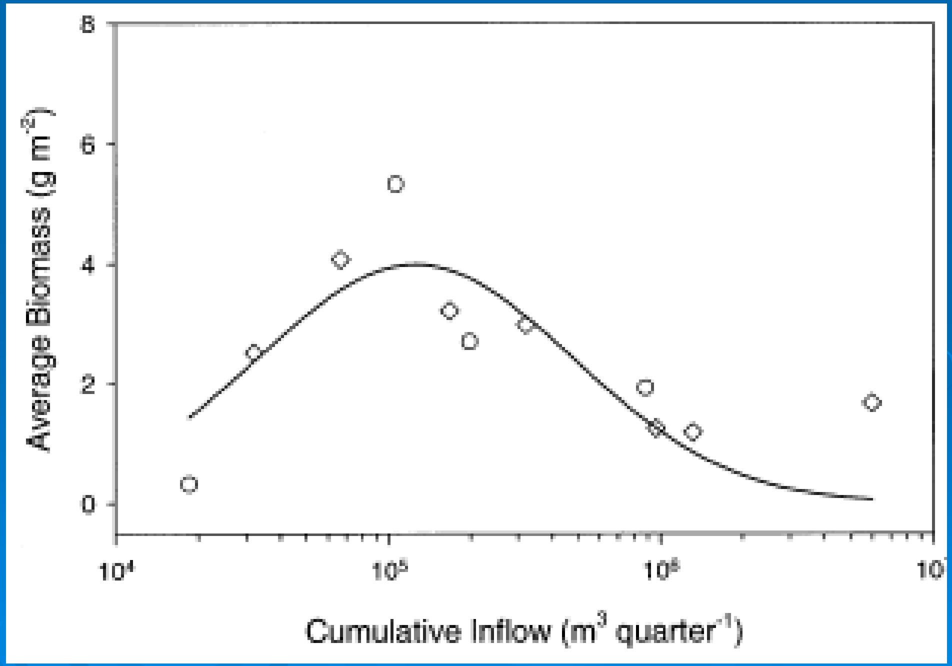
Phytoplankton biomass in positive estuaries is supported by “new” nitrogen (DIN) from riverine input, but high concentrations of “old” nitrogen (DON, ammonium) supports high chlorophyll in the negative estuary

Key Findings Over 30 Years - Sediment

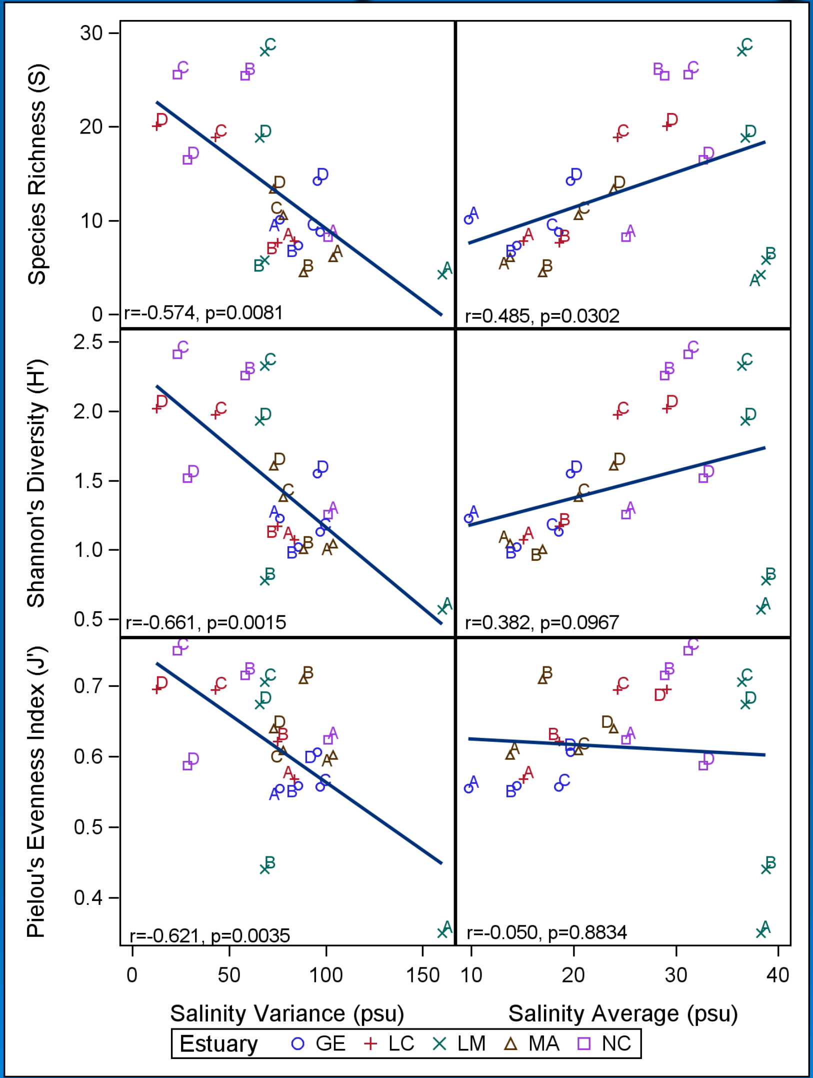


- Benthic abundance, biomass, and diversity peaks at mid-salinity ranges (left), and inflow ranges (right)
- Estuaries, 2002, 25(6B): 1436-1447

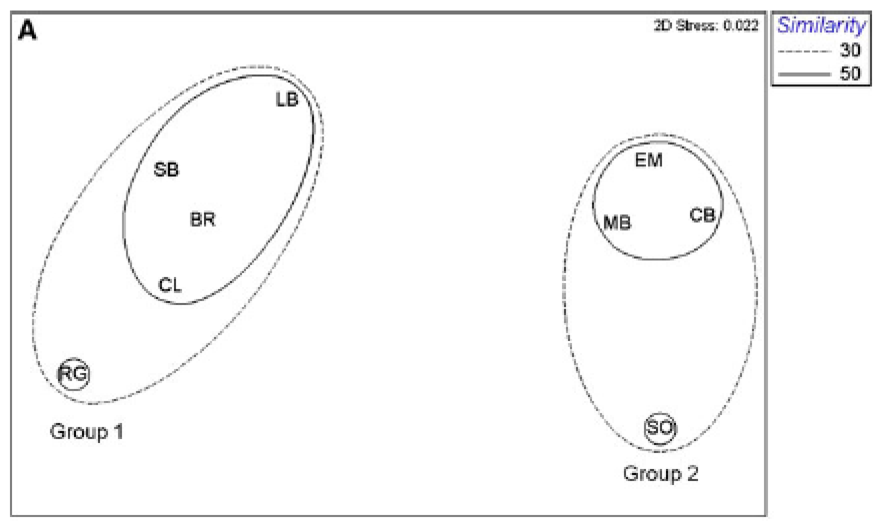
Nueces River flowing into Nueces Bay



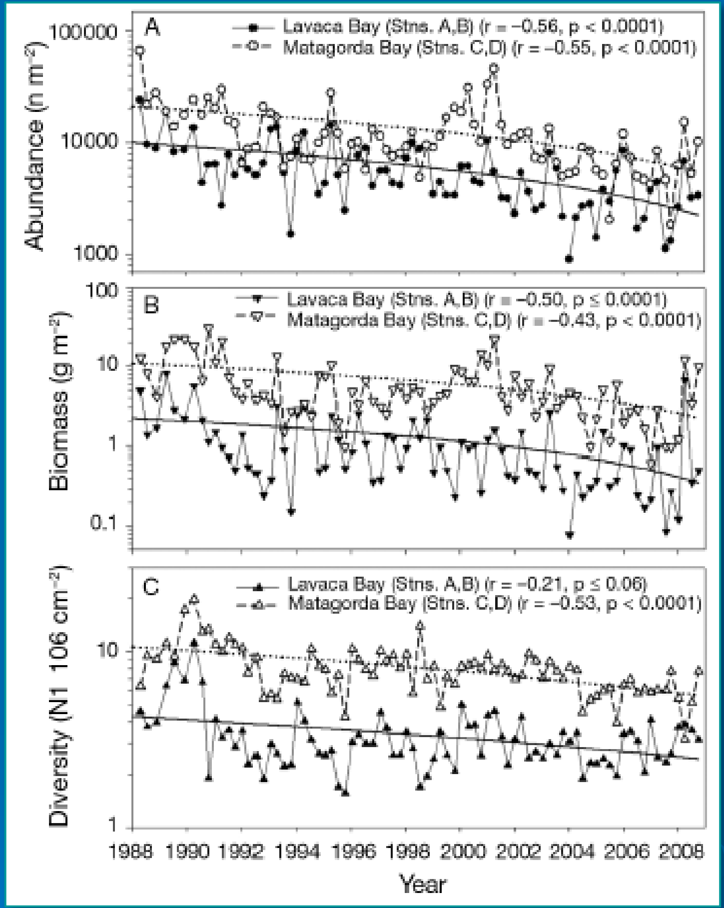
Key Findings Over 30 Years - Sediment



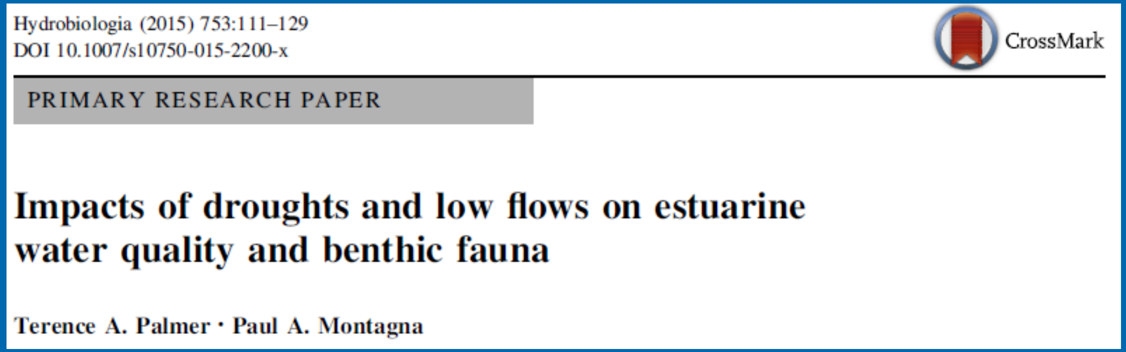
Salinity variability drive diversity (*Estuaries and Coasts*, 2016, 39:967-980)



Primary bays near GOM (Group 2) have different community structure than secondary bays near rivers (Group 1) (*Hydrobiologia*, 2011, 667:49–67)



Benthos are declining dramatically in the Lavaca-Colorado Estuary, Texas (*Mar Ecol Prog Ser*, 2011, 436:67-80) and other estuaries

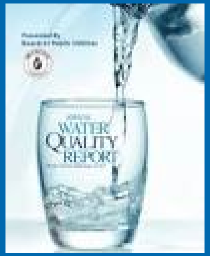

Hydrobiologia (2015) 753:111–129
DOI 10.1007/s10750-015-2200-x
CrossMark
PRIMARY RESEARCH PAPER

Impacts of droughts and low flows on estuarine water quality and benthic fauna

Terence A. Palmer · Paul A. Montagna

Effects of Droughts in 8 Texas Bays

Water Quality



Nitrate + Nitrite ↓
Reduced loading

Chlorophyll ↓
Reduced nutrients

pH ↓
Reduced photosynthesis

Shrimp

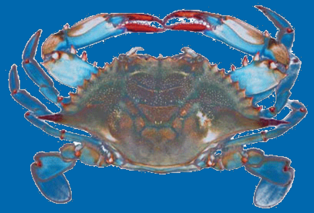
Abundance ↓

Size (length) ↑

Juvenile Abundance ↓

Juvenile % ↓

Blue Crabs



Abundance ↓

Size (width) ↑

Juvenile Abundance ↓

Juvenile % ↔