Overcoming Object-Relational Impedance Mismatch in GIS Development: a Comparison of Data Abstraction and Serialization Methods used in Web Mapping Application Development

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Abstract

This paper presents two data access strategies that employ different data abstraction and serialization methods applied to a working geodatabase to facilitate development of a web mapping application. The goal of the study was to compare methods used to minimize the effects of object-relational impedance mismatch, a well-known set of issues that result from the integration of relational data and object-oriented programming languages. This study focused specifically on increasing support for schema evolution; a common object-relational impedance issue within GIS systems. The study was conducted using a real-life, transactional geodatabase used to maintain water quality data. The database and test applications were designed to meet real-life functional requirements. The first method employed the use of entity modeling techniques in the application mid-tier to map relational geospatial data from the relational database management system to an object-oriented model in order to facilitate data access, serialization and transport via a web service; the second procedure maintained application logic within the object-relational geodatabase system tables and employed a generic abstraction method for serialization within a web service. The resulting n-tier applications were tested by applying a unit test strategy based on real-life use case scenarios and the results were compared to assess the extensibility, maintainability and richness of the result. The application that leveraged the object-relational model of the geodatabase system was found to provide better support for schema changes to the geodatabase resulting in less maintenance, while the application constructed using entity modeling of relational data resulted in richer UI features but was not able to support schema changes to the geodatabase.

Introduction

Relational databases are a widespread storage format for geospatial data. Commonly used development frameworks for web mapping solutions are designed for object-oriented development. A well-known set of problems, commonly referred to as *object-relational impedance mismatch*, occur when applications are developed using object-oriented concepts to access data persisted in relational databases. Due to the increasingly widespread implementation of service-oriented (SOA), multi-tier (also

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known as n-*tier*) architecture there is an increased need to improve the interoperability, and extensibility of data access services. This need is also present within GIS application development where data services are often used to provide access to relational schema that undergo periodic database refactoring as geodatabase schema evolve over time.

According to Ambler (1998), object-relational impedance mismatch is defined as follows: "The difference resulting from the fact that relational theory is based on relationships between tuples (records) that are queried, whereas the object paradigm is based on relationships between objects that are traversed". Interoperability of these systems is often achieved through the implementation of object-relational mapping (ORM). ORM is the process of mapping objects to relational data in order to overcome the impedance mismatch. N-tier applications are applications where presentation, service, business logic and data tiers are logically and sometimes physically separate. In n-tier applications the ORM process occurs within the mid-tier, between the data and service tiers. This often results in common language runtime (CLR) objects. Relational data are abstracted into objects that integrate easily with popular object-oriented languages. The purpose of entity modeling within this process is to project data from a logical relational model to an object-oriented language. This results in compiled, object-relational mappings that can be queried and manipulated using object-oriented languages, often from multiple application tiers.

Entity modeling is a form of ORM that raises the level of abstraction within the mid-tier. In an entity data model (EDM), entities and associations can be used to represent conceptual, as opposed to relational, models as they are abstracted into objects. Entities represent top-level objects, for example a row or a tuple, with identities, while associations are used to relate two or more entities (Adya, A., et al., 2007). In n-tier development the objects that result from EDM provide better multi-tier access since these objects can be serialized using an interchange format such as XML or JSON for web service invocation and desterilized within the presentation (client) tier as needed. The study described in this paper uses an Entity Data Model (EDM) as a means of object-relational mapping.

Unfortunately, ORM/EDM does not entirely overcome the impedance mismatch problem. Although EDM frameworks like the Microsoft ADO.NET Entity Framework, were designed to reduce object-relation impedance mismatch as it relates to code semantics and inefficiencies (Adya, et al., 2007), some definitions of object-relational impedance mismatch identify ORM/EDM as a cause of impedance mismatch, rather than a solution (Chen and Huang, 1995); especially when mappings between objects and tables are made in a very straightforward way (Wikipedia, 2010). This is because when the relational schema changes, which can be quite common in transactional GIS systems, the relational model and the object model become inconsistent and the mapping between the two models must be updated to maintain synchronization. In an application with ORM CLR objects, synchronization would require code changes and recompilation of the ORM assemblies. Although, methods have been proposed for maintaining the consistency of these mappings under database evolution (An, et al., 2008), these methods are quite complex and difficult to implement without an existing framework in place.

One alternative to ORM is to employ an Object-Relational Database Management

System (ORDBMS). ESRI's geodatabase is an ORDBMS. It essentially consists of a RDBMS core with an object-oriented shell or layer through which applications access and manage persistent data. The object-oriented model within the RDBMS consists of a series of relational tables, referred to as the Geodatabase System Tables, which hold data used to instantiate objects. Metadata for all objects within a geodatabase, for example feature classes, tables and relationships classes, is persisted in the Geodatabase System Tables. Relational GIS data is stored within the RDBMS within a set of business tables. In ORDBMS, object-oriented programming concepts such as polymorphism and inheritance result in advantages for application developers and tend to minimize object-relational impedance mismatch (Worboys and Duckham, 2004).

One way ORDMSs reduce impedance mismatch is by increasing support for schema evolution. A common feature of object-oriented systems is schema management including the ability to create and change class schemes (Worboys and Duckham, 2004). This feature is part of ESRI's Geodatabase System as well. It is apparent in the ability of GIS practitioners to administer schema changes using ArcGIS data management tools. Typical ESRI Geodatabase client applications like ArcMap are able to support schema changes to underlying databases due to the object-relational model employed by the system. Consider the example of relationships between spatial features. These relationships are defined within the geodatabase as a relationship class object. In this way new relationships can be defined at any time. GIS client applications are built using ArcObjects to interface with the objects defined within the GDB System Tables. As a component of the object-relational GIS system, they are able to support schema changes and evolve as the underlying geodatabase changes without the need for code maintenance.

Although ArcObjects are a viable and supported solution to the issues of impedance mismatch, third party Applications Programming Interface (API) dependence is an issue for several reasons. The ArcGIS Server Web APIs that have been developed to work with the ESRI GIS systems have limited access to fine-grained ArcObjects within the service, and presentation tier of n-tier technology such as Silverlight. It is also documented that application performance is adversely affected by frequent calls to fine-grained ArcObjects (Laframbiose, 2006; Flood, 2002). In addition, Silverlight was developed to mesh seamlessly with ADO.NET Entity Framework, a robust EDM solution, as well as SOA frameworks, making an ArcObjects-free solution appealing. For these reasons, there is a need to investigate alternate solutions that overcome the object-relational impedance mismatch without heavy reliance on proprietary APIs.

Some strategies for minimizing impedance mismatch leverage RDBMS programming languages such a Transact-SQL (TSQL). As Zdonik and Maier (1990) point out: "a loss of information occurs at the interface, if the programming language is unable to represent database structures, such as relationships, directly." This is essentially what happens when the objects and the relational model, joined by an ORM, become out-of-sync due to schema changes to the relational model. Zdonik and Maier (1990) imply that impedance mismatch is proportional to the amount of interface that occurs between the relational and object-oriented components of the application, therefore, maintaining more of the application within one system would lower impedance mismatch. Although not entirely computationally complete when compared to an object-oriented language, stored procedures and TSQL come very close. Implementing stored procedures that navigate the ArcSDE System Tables to provide access to objects would likely overcome many of the impedance mismatch problems that occur within GIS systems and result in a solution that can support schema changes.

In addition to leveraging RDBMS languages such as TSQL to reduce impedance mismatch, others have suggested using loosely-typed object mappings to increase "data independence" within systems (Bernstein, et al., 2008). This differs from typical EDM strategies where relational schema is mapped to strongly-typed CLR objects. This concept could be implemented within the mid-tier of the application as a way of exposing data to client applications via web services without creating hard-coded objects that are dependent on explicit data structures. The result would be more capable of supporting schema changes.

Data

Water Quality Database

Several years' worth of water quality data has been collected by specialists within the city of Eagan, Minnesota and has resulted in a robust geodatabase that is primarily maintained and developed by water quality staff with knowledge of ArcGIS and Geodatabase schema management techniques. The database consists mainly of water body feature classes; lakes, wetlands, and storm basins, and related water quality data stored within stand alone tables. Relationship classes are defined to relate the water body features to the standalone tables, typically in a one-to-many specificity. Attribute domains are used where ever possible to maintain the integrity of the tabular data.

The Water Quality geodatabase runs on ArcSDE 9.3.1 and Microsoft SQL Server 2008. A geodatabase data model diagram of the water quality database is displayed in Appendix 3.

Methods

Application Development Objectives

There were two primary objectives considered when developing the study applications. As stated earlier, the first objective was to maintain the level of schema management afforded by ArcGIS, while minimizing or eliminating the need for code or relational mapping maintenance and application recompiles. The second was to improve the end user experience for users who have limited GIS knowledge and who would primarily be viewing data related in a one-to-many cardinality to water body features in the Geodatabase. In addition, typical web mapping application development objectives were upheld.

Limitations

Since the intent of the case study application was to provide an interface for internal employees to access the water quality database and not individuals from the general public, security was not a consideration during the development of the services or application.

Additionally, the geodatabase versioning workflow used by staff to maintain the water quality data was simplistic and implemented the option to move edits to base tables. For this reason, there was no need to consider more complex versioning scenarios within this study.

Development Methods

Both study applications used in this comparison were developed using C# and Microsoft .NET 4.0 within the Microsoft Visual Studio 2010 Environment. The .NET framework was selected as the platform for development for several reasons. Mainly, the .NET framework includes well documented and easily integrated frameworks for developing each tier of the study application including EDM, web data service development (Klein, 2010), as well as client interface development and automated unit testing (Ghoda, 2010).

The presentation layer, a portion of client-tier, for both study applications was developed using consistent methods. Both client-tier applications were developed using Microsoft Silverlight version 4.0. The client-tier consists of a map-centric user interface (UI) constructed using the ArcGIS Server API for Microsoft Silverlight 2.0. A simple ArcGIS Server web mapping service was used to publish the water body features (lakes, storm basins and wetlands) as a single service. The service was consumed within the ArcGIS Server Silverlight map control. Both applications included traditional GIS “identify” functionality. The interface also contained a Silverlight tab control designed to display a series of data grids that hold records related to the water body features. The data grids were populated with related records based on the results of an identify event.

Application 1

Application 1 employed a data access strategy that was developed using an entity model in the mid-tier to map data from the business tables of the waters geodatabase to data objects used within the application. Figure 1 depicts Application 1 as an n-tier application with an Entity model represented within the mid tier and client tiers.

The EDM of the water quality geodatabase was designed using Microsoft ADO.NET Entity Framework data modeling tools. The water quality database feature classes, tables and relationship classes were redefined within the entity model context.

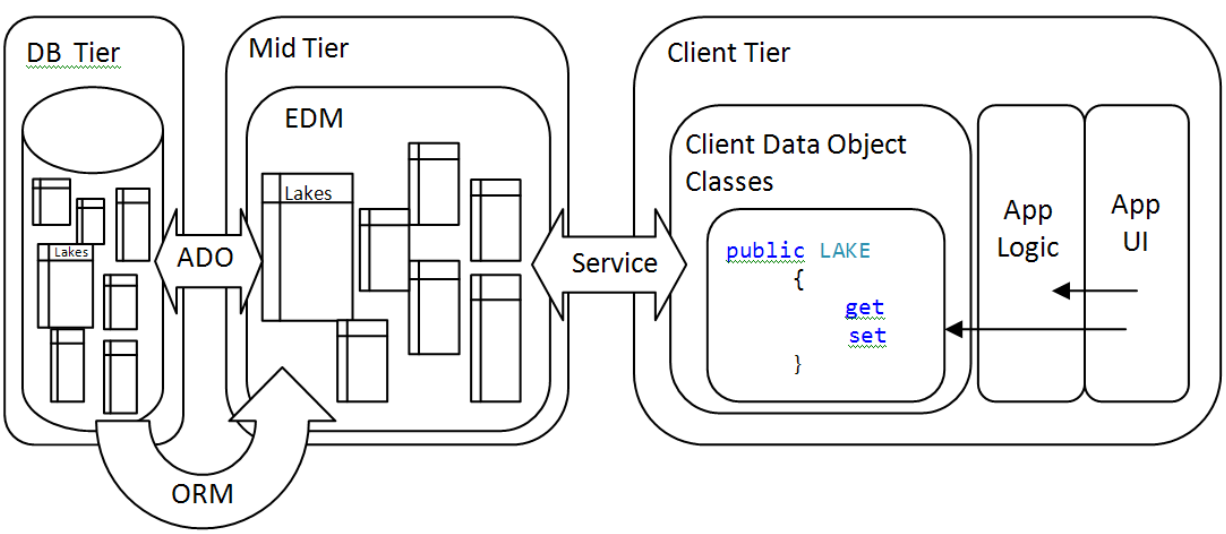

Figure 1. Application 1 n-tier diagram.

Associations between feature class business tables and standalone tables were defined based on the characteristics of existing relationship classes within the geodatabase. The cardinality of each relationship was defined within the multiplicity property of the association. Appendix 1 illustrates the structure of the lakes entity object. Wetlands and storm basin entity types were created using similar methods.

This process resulted in a series of .NET classes that defined strongly-typed objects known as entity types. Each entity type mapped a feature class to its associated tables. Data in the tables was accessed through properties and methods of the entity type.

A type of Windows Communication Service (WCF) web service, specifically a Domain Service, was used to expose the entity model. WCF Data Services expose data, often represented as EDM entity objects, via web services accessed over HTTP. In addition to exposing data over HTTP, WCF Domain Services manage the serialization of data objects between the server-side (mid-tier) and the client-tier. The Domain Service that was implemented within Application 1 enabled the query of EDM types via domain context objects. Context objects could be considered a "mirror image" of the EDM objects on the client. The resulting server-side and client-side classes enabled the query of data via strongly-typed CLR object instances of the entity types from multiple application tiers.

Application logic was added to the domain service class so that data operations could be exposed through the service. Since the backend geodatabase included aliased fields, business logic was added to the client tier to accommodate functionality within the EDM Domain Data Service context.

Application 2

Application 2 was designed to demonstrate the use of TSQL and generic data services to eliminate object-relational impedance mismatch within the application. Rather than creating mapping between the business tables within the relational geodatabase and an object-oriented language, in Application 2 objects were accessed by querying the geodatabase system tables using TSQL. Since ArcObjects were not readily available for development within the web tier of the application, an equivalent set of objects needed to be developed to provide access to the data within the object-relational model. This was accomplished using a custom data access layer that navigated the relationships defined within the geodatabase system tables and acted as a means of interfacing with the objects stored within.
Figure 2 shows the n-tier application logic developed within Application 2.

The business logic within Application 2 resides within the database as a pair of stored procedures that query the geodatabase system tables that hold objects defining relationship classes, tables and field information. Figure 3 depicts the structure of GDB systems tables queried within the custom stored procedures.

The first stored procedure accepts a layer name as a parameter and returns a list of relationship class names where the identified layer is the origin object class. The second stored procedure accepts the object ID of a spatial feature and the name of a relationship class object, for example "Lakes_has_Inspections" and returns a table of related values. The stored procedures are designed to be called through a web services by the client-tier. Table 1 describes input parameters and results of each stored procedure.

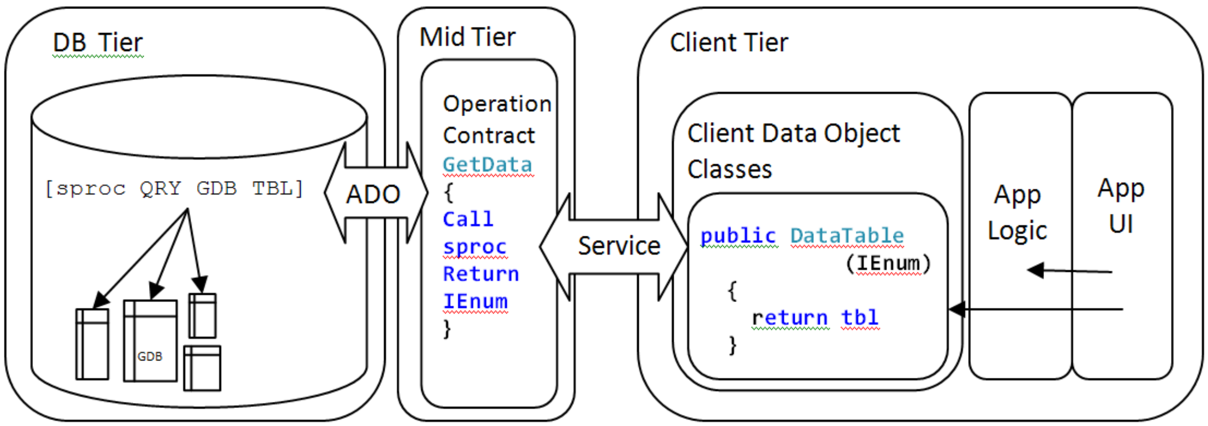

Figure 2. Application 2 n-tier diagram.

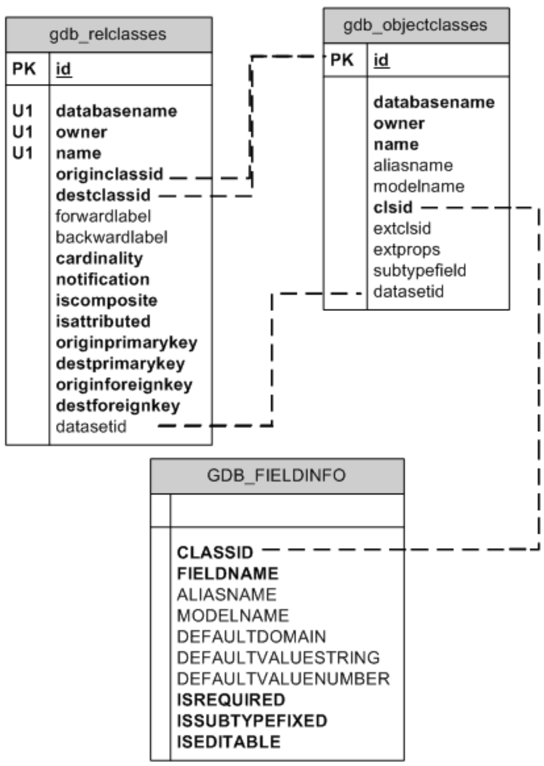

Figure 3. Geodatabase system tables used by Application 2.

The application logic within the client-tier of Application 2 was designed to query the first stored procedure to get a list of relationship classes related to the identified feature and then used the resulting list to recursively query the second stored procedure to retrieve tables of records related to the feature.

Table 1. Stored procedure inputs and results.

Stored Procedure	Input Parameters	Result
ListRelates	Featureclass name	A table containing a row for each relationship with a single column; RELATIONSHIPNAME
QueryRelated	Relationship class name ObjectID	Anonymous table of related results.

The data access layer consists of a WCF service with a very simple generic operation contract, “GetData”, through which the stored procedures are queried by the client-tier. This is accomplished by making a call to the stored procedure, and then casting the results to an anonymous .NET IEnumerable object. Generally speaking, an IEnumerable object consists of a collection of collections. In this case each enumerable consists of a set of key-value pairs; fieldname, field value. The enumerable object is then serialized for transport to the client-tier. The code in listing 1 shows a portion of the operation contract for the service. The GetData methods accept a query parameter which contains a query used to execute one of the stored procedures.

Listing 1. Code sample from the operation contract of the web service used in Application 2.

```
namespace Application2
{
    [ServiceContract(Namespace = "")]
```

```
    public class MyService
    {
        [OperationContract]
        public
IEnumerable<Dictionary<string, object>>
GetData(string query)        {
            var table =
GetDataTable(query);
            var columns =
table.Columns.Cast<DataColumn>();
            return
table.AsEnumerable().Select(r =>
columns.Select(c =>
             new { Column =
c.ColumnName, Value = r[c] })
            .ToDictionary(i => i.Column,
i => i.Value != DBNull.Value ? i.Value :
null))
        }
```

On the client-tier, a custom class was included to iterate the enumerable objects returned by the service in order to recreate a datatable from it. The resulting datatable object is used within the user interface application logic. If the request sends a query string to query the second stored procedure for related records based on a relationship class, the result will be bound to a Silverlight data grid control.

Analysis Methods

Both applications were tested by implementing a set of real-life use case scenarios, designed to uphold development objectives. The performance and code maintenance requirements of the two study applications were assessed by implementing an automated black-box type testing created using the Microsoft Silverlight Unit Testing Framework.

Use Case Scenario

Both applications were tested based on a typical use case scenario modeled in figure 4, which was designed to verify that the functional requirements and development objectives were met.

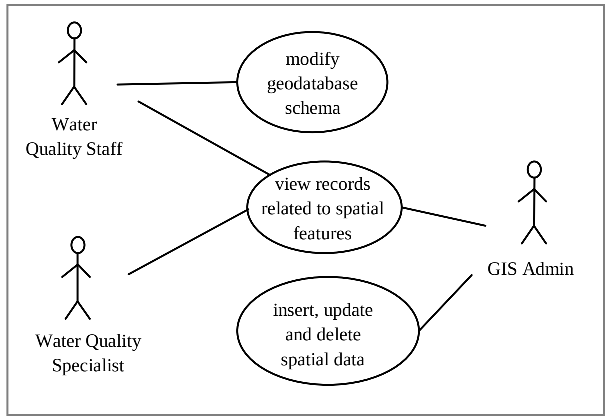

Figure 4. Use case model depicting primary actors within a GIS system and tasks performed.

The use case diagram shown in figure four illustrates the actors and the tasks that each actor would carry out within the GIS system. Table 2 details what applications were to be used by each actor to carry out GIS tasks displayed in the model. Both of the study applications were intended for use by water quality staff to query data while the ArcGIS desktop applications were used to perform other GIS tasks like schema management.

In conversational form, a typical use case outline for either of the study applications would occur as follows:

- Actor 1 (a water quality staff member) runs the application from a known URL and is presented with a map displaying the spatial locations of water body features within the city.
- Actor 1 navigates the map using typical web map navigation key clicks and identifies a water body feature of interest.
- Actor 1 uses the cursor to click on a water body feature and is presented with data within a tab control. Each

tab presents one or many records from a single table related to the selected water body. There is one tab for each relationship class defined within the geodatabase for the selected feature class.

Table 2. Tasks performed by use case actors.

Actor	Application Used	Task
(Actor 1) WQ Staff	Study Applications 1 & 2	Query spatial features to view related records for past inspections, WQ test, and work orders.
(Actor 2) GIS Admin	ArcGIS	Administer schema changes to geodatabase including adding or deleting columns, tables, and relationships as the database evolves.
(Actor 3) Water Specialist	ArcGIS	Add spatial features and records to WQ database to document tests, inspections, and work orders.

Both web applications were tested using the use case model described above and assessed for performance. Insert, update and delete operations as well as schema changes to the geodatabase were performed using the ArcGIS Client applications. Table 3 lists the order of the staged schema changes and unit test rounds.

The order of the tasks above was intended to inclement the amount of impact made on the geodatabase schema in order to test the individual affects of various schema changes.

Testing

A black-box type testing strategy was designed to compare the performance of the two applications under schema evolution. Black-box testing (also called functional testing) is testing that ignores the internal mechanism of a system or component and focuses solely on the outputs generated in response to selected inputs and execution

Table 3. Detailed, ordered task list for testing study applications.

Testing Stage	Application Used	Task
Stage 1	Apps 1&2	Test functionality via unit tests with no changes to database.
Stage 2	ArcGIS	Add 2 features to the Lakes Featureclass.
	Apps 1&2	Test functionality via unit tests.
Stage 3	ArcGIS	Add a new column to the alumtreatments table.
	Apps 1&2	Test functionality via unit tests.
Stage 4	ArcGIS	Add new standalone table and relationship class relating Lakes, Stormbasins, and Wetlands to the new table.
	Apps 1&2	Test functionality via unit test.

conditions (IEEE, 1990). The tests were automated using a unit testing framework and were run under controlled conditions. Each test was designed to emulate an identify event within the application, sending in known parameters and testing the ability of the application to display the results. A series of mock objects were used to imitate each valid set of identify results; i.e., one mock object for each water body feature (n=834 at stage 1). Fault detection within the testing application was limited to a simple pass/fail.

The testing was performed after a series of stages designed to emulate schema evolution in a geodatabase resulting from the aforementioned use cases.

Results

Tables 4 through 7 show the results of the automated tests for each of the study applications during each stage of the testing.

Table 4. Unit testing results for stage 1.

Application	**Pass/Fail**	**Average Time to Execute** (µs)
Application 1	834/0	38275
Application 2	834/0	23881

Table 5. Unit testing results for stage 2.

Application	**Pass/Fail**	**Average Time to Execute** (µs)
Application 1	836/0	37568
Application 2	836/0	24227

Table 6. Unit testing results for stage 3.

Application	**Pass/Fail**	**Average Time to Execute** (µs)
Application 1	809/27	37986
Application 2	836/0	24992

Table 7. Unit testing results for stage 4.

Application	**Pass/Fail**	**Average Time to Execute** (µs)
Application 1	0/836	36487
Application 2	836/0	23129

Both applications performed well during stage 1 and 2. Both passed 100% of tests run against 834 (stage 1) and 836 (stage 2) mock objects. During stage 3, Application 1 failed 27 of 836 tests while Application 2 passed all tests.

The average executing time is indicative of execution under "best-case" circumstances since the client application and service were all running on the same workstation, eliminating network factors. The difference in execution times between tests run against Application 1 and Application 2 was not large and so, generally speaking, was similar between the two applications.

Discussion

Test Results

The 27 failed tests that occurred after the insertion of a new column in the alum treatments table likely occurred because 27 water body features had related alum treatment records and none of the alum treatment query results reflected the changes to the underlying data table. This is an indication that the object-relational mapping of the EDM is out of sync with the relational data structure. The number of tests failed by Application 1 increased in stage 4 because the addition of a new table and relationship classes had a larger impact within the database; affecting more features.

Throughout the testing Application 2 continued to perform well. Changes made to the schema of the relational geodatabase were reflected in the query results displayed within the application. Application 2 was made "aware" of these changes in the same way that an ArcGIS desktop application does, by querying objects stored in the GDB system tables.

Considerations

Some features common to both applications enhanced their ability to accommodate schema changes. One important feature of Silverlight is the ability to auto-generate columns when binding data to a data grid. Doing so reduces the level of dependence the application code has on the data structure since no column names were referenced within the code.

Although the unit testing results indicated that Application 1 failed several tests due to schema changes to the underlying database, it is relevant to discuss the definition of a failed test within this study. The testing strategy used within this application was designed to fail if a test result did not reflect accurate results based on the underlying geodatabase design. This is noteworthy because in traditional development terms the application may not have actually thrown an exception in all cases. Due to the way that the EDM model was used to query the database, an exception may not have been thrown if a column was added to a table that was abstracted within the entity, since the entity type doesn't possess a property that maps to the column. Additional ad hoc testing indicated that an exception would be thrown only if a column or table that was mapped to an existing entity property was deleted. In this way, the EDM approach to data access may be a good fit for some GIS systems needing to improve the level of support for schema changes. However, this does not provide the level of support for schema changes needed to meet the development objectives of this study.

Although Application 2 proved better able to support schema changes, the strongly-typed data mapping features of the EDM used in Application 1 are noteworthy. The data features of EDM and Silverlight make it easier to incorporate rich UI features like better data validation on the client-tier. For example, prebuilt Silverlight controls, like the calendar control, depend on explicitly defined field types like date fields. This level of data validation was not easily incorporated within Application 2 due to the generic nature of the data objects.

There were also some notable disadvantages to leveraging the geodatabase system tables that became evident in the development of Application 2. The issues encountered were primarily caused by the complexity of the geodatabase system. One example of this is apparent when examining the graphic in Appendix 2, which shows a display of the completed water quality application (Application 2). Note that there is a tab in the tab control and table populated with related data based on a relationship class used to facilitate feature-linked annotation. This was not a desirable outcome. Additional logic would need to be added to the stored procedures to exclude this type of relationship.

Conclusion

Leveraging the ESRI object-relational geodatabase model in GIS application development can provide a means of accommodating schema evolution that commonly occurs within a GIS system. Stored procedures and TSQL have proven to be an efficient method for querying the geodatabase system tables while minimizing the amount of impedance mismatch within the object-oriented code. The explicit configuration used within EDM results in greater dependence on the underlying relational data structure and additional code maintenance is needed to support schema changes.

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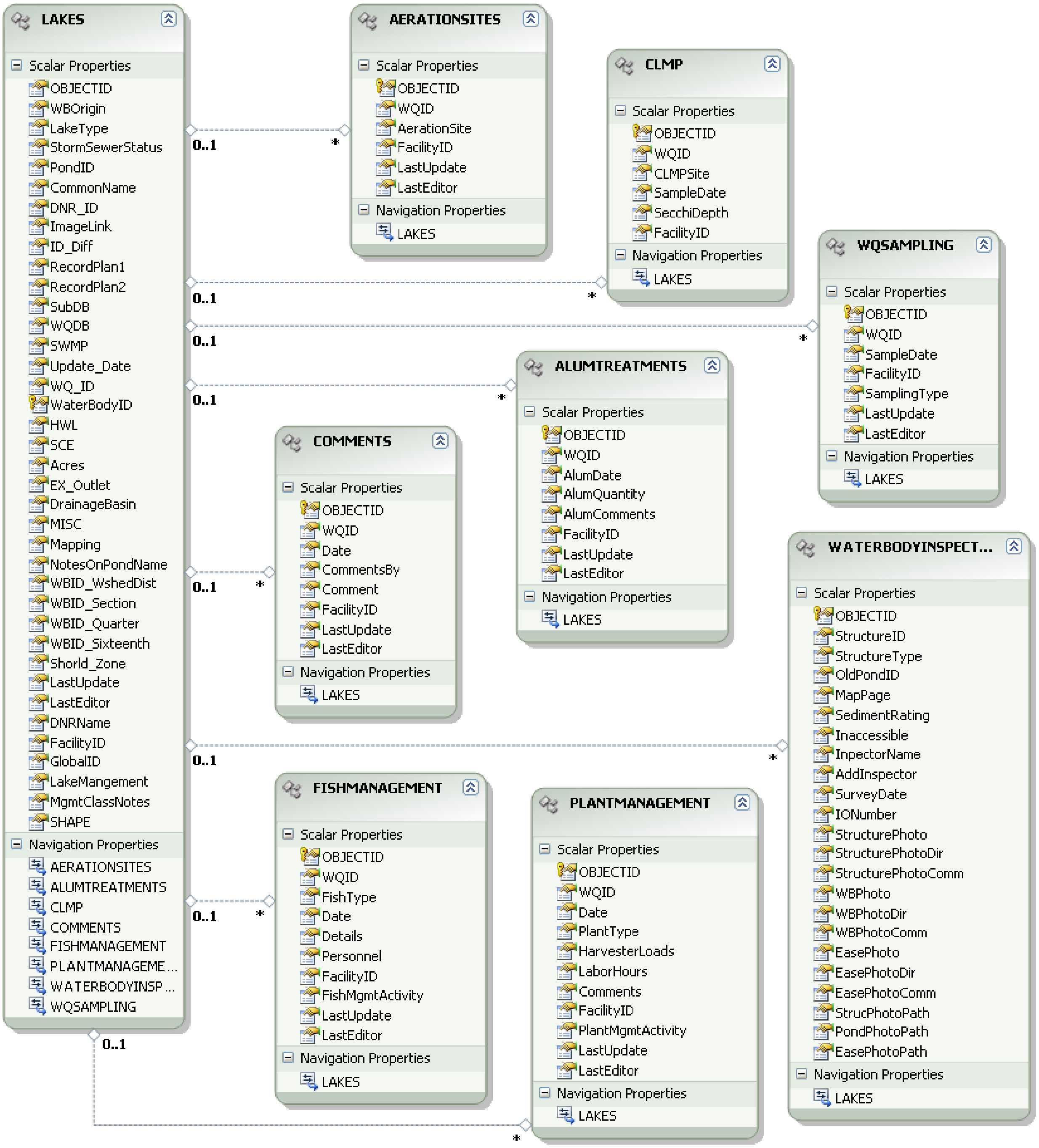
Appendix 1. Entity model diagram of the LAKE entity.



Appendix 2. A graphic display showing the completed Water Quality Application 2 with the results of an "identify" operation.